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INVESTIGATIONS INTO THE FATIGUE

OF

CYLINDRICAL SPIRAL SPRINGS

FOR

AEROPLANE ENGINES.

By

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Thesis for the Degree of Ph.D.

C O N T E N T S.

INVESTIGATIONS INTO THE FATIGUE OF CYLINDRICAL SPIRAL SPRINGS FOR AEROPLANE ENGINES.

INTRODUCTION.

This research was instituted originally in 1922 at the request of the Aeronautical Research Committee, owing to the number of valve spring breakages in certain aeroplane engines, and to the lack of definite knowledge of the effect of repetition of stress upon steel when coiled into a spring.

At the instance of Professor Sir Thomas Hudson Beare, to whom the Committee's request was made, the work was undertaken by Mr G. Hume Fleming, B.Sc., and was carried on by him until 1923, when he left to take up an appointment abroad.

During the years 1924-25, some little attention was given to the matter by the Mechanical Engineering Assistant in the Department of Engineering, Mr A. T. Bowden, B.Sc., without, however, any definite results being recorded.

The recording of the preliminary work due to Mr Fleming has been dealt with as follows:-

Supply of material; tension and torsion tests on the wire itself; static compression tests on the springs; the original design of the apparatus for fatigue testing - described on pages 5 to 9.

Description of two of his fatigue tests - pages 11-13.

Tabulation of the results of his static compression tests - Table 3 at end of thesis.

Tabulation of the results of all his fatigue tests - Tables 4 and 4(a), at end of thesis.

Mr Fleming's intention was to endeavour to derive some formula founded on the results of the tests, whereby the spring dimensions suitable for given working conditions could be calculated. His fatigue tests, however, yielded no definite results, and in the meantime the work of various investigators had gone to show that the derivation of any formula of general application was hardly feasible, a statement now borne out on bringing the present tests to a definite conclusion.

The following is a brief statement of accepted knowledge of the fatigue of metals, relevant to the case of spiral springs.

For all ferrous metals there exists a definite limiting range of stress, generally known as the "Fatigue Range". A metal, subjected to a range of stress of magnitude very slightly below this Fatigue Range, will endure an infinitely large number of reversals (N) of this stress (S) without failure, i.e., the range of stress is a "safe range". On the other hand, if the range of stress is of magnitude very slightly in excess of the Fatigue Range - i.e., it is an "unsafe range" - it has been found that failure almost invariably occurs within the limit of 10^7 reversals of stress. The "S"/"N" curve - and more definitely - the log "S"/log "N" curve clearly indicate this by becoming horizontal in the neighbourhood of (N) = 10^7 reversals. That is to say, for all practical purposes the fatigue range of a ferrous metal may be determined by tests carried out on a 10^7 reversals basis.

There are other factors, however, which may influence the endurance of the metal, i.e., other than the range of the stress repetitions to which it is subjected. Those which may have an effect upon the metal in any manufactured form are:-

(a) Surface Conditions.- In general, scratches left by ordinary shop processes may result in a decrease of the fatigue range of the metal amounting to as much as 30 per cent.

In the particular case of springs, premature failure may occur from surface defects produced in the manufacture of the wire itself. Grinding of the wire before coiling may obviate these original defects; but the coiling and subsequent heat treatment are liable to produce further defects in the material, with a consequent lowering of the fatigue range.

(b) "Under-stressing" and "Over-stressing" Effects.- The former effect is obtained by subjecting the metal to repetitions of, generally, a "safe range" of stress, and thereafter "loading up" to successive higher ranges.

For /

For example, suppose a specimen endures 10^7 reversals of a certain range of stress (say 19.6 tons/sq.in). The range is then increased to 19.8 tons/sq. in. and a further 10^7 reversals are endured. This process is repeated, increasing the range of stress by increments of 0.2 tons/sq.in., until failure occurs.

Although the actual value of the fatigue range may be (say) 20 tons/sq.in., the "under-stressing" effect will be found to have raised it to a value notably in excess of this; possibly as much as 30 per cent in excess.

It is clearly futile to endeavour to determine the fatigue range of a metal by testing a single specimen to destruction by this system of "loading-up".

The "over-stressing" effect is obtained by subjecting the metal to repetitions of an "unsafe range" of stress. The primary effect of this fatigue of the metal is to produce "slip". This is essentially a hardening effect. Thereafter, the "cracking" stage is reached, wherein the crack, or cracks, ultimately produce failure.

In the case of an over-stressed specimen, if the range of stress is reduced by successive decrements before the repetitions of any of these ranges of stress have caused the metal to pass the "slip" stage, the fatigue range will not be appreciably affected.

On the other hand, if the repetitions of any unsafe range are prolonged so as to cause the metal to enter the "cracking stage", then the fatigue range will be lowered.

(c) <u>Speed Effect</u>.- Within the limit of 7000 cycles per minute it has been definitely established that there is no "speed effect", <u>i.e</u>., that the speed of repetition of the range of stress has no effect on the fatigue range.

(d) /

(d) Machine Effect.- It is necessary to exercise care that, in the method of testing adopted, stresses peculiar to the particular type of machine are not induced in the test-piece, thereby seriously affecting the results obtained.

Surging.- This is a phenomenon peculiar to valve springs, due to the spring being forced to oscillate, by the action of the cam, at other than its natural period for the given load. The spring is said to be "surging" when the oscillations of the coils during a revolution are observed to travel along the spring in the form of a definite wave.

The speeds at which these oscillations are greatest are known as "synchronous speeds", identification of the precise speed for synchronism being aided by the fact of the spring giving out a definite musical note at this speed, if the oscillations are fairly large.

The effect of these oscillations is to set up unequal strains in the spring, in addition to the uniform strain equal to that of the cam motion. The resultant stresses may be very large, and it is undoubtedly due to this surging effect that valve springs fail although apparently operating at stresses very much less than the fatigue range of the metal.

Creep.- Designates the shortening, or "set", of the spring under load. This "creep" should be as small as possible, and may be expressed as a stress which would be produced in the spring by an alteration in length equal to the amount of set. The Modulus of Rigidity is assumed to remain constant.

RANGE OF INVESTIGATIONS.

The tests come under three headings, viz.:-

(1) Tension and torsion tests on the wire itself.
(2) Static compression tests on the springs.
(3) Fatigue tests on the springs.

As already stated in the introduction (p.1), the tension and torsion tests on the wire (Tables 1 and 2) were carried out by Mr Fleming, as were also a few fatigue tests, the results of which are given in Tables 4 and 4(a) at end of thesis.

In the fatigue tests it was originally intended to test the springs in three groups, viz.:-

(1) By varying the cam-shaft speed between 900 and 1100 r.p.m.

(2) " " " cam lift between 5/16" and 7/16".

(3) " " " temperature of the springs between normal temperatures and 200° C.

As regards Group 1, the knowledge gained in the meantime of the absence of "speed effect" removed the need for any work in that direction.

Temperature tests (Group 3) could not be usefully proceeded with, owing to the springs available for the tests not being suitable for working at high temperatures.

Accordingly, the work done has been confined almost entirely to Group 2, in the first instance using cams of 5/16", 3/8", and 7/16" lift respectively, and latterly with the addition of a similar cam of 1/2" lift.

MATERIAL.

The material used in these tests is hard-drawn steel wire of 0.83 per cent Carbon content, supplied by Messrs Bruntons, Musselburgh. The process of manufacture was as follows - "The material was heated considerably above the recalescence point; then cooled at such a rate as to produce a pure sorbitic structure. Thereafter it was cold-worked."

The /

The wire was supplied in three sizes, viz., 5/32", 1/8", and 7/64" diameter. It was coiled into springs by Messrs Terry, Ltd., Redditch, without further heat treatment, in order that the properties of the material as springs might be identical with that of the uncoiled wire.

Preliminary tests in tension and torsion were carried out on the wire itself, the average results for each size being given in Tables 1 and 2 (below).

With regard to the tension tests, Young's Modulus (E) could not be accurately determined owing to the great difficulty experienced in making the wire initially straight. The tension experiments were carried out on a small 10,000 lb. "Olsen" machine, and the torsion experiments on a small laboratory torsion-testing machine, originally supplied by Messrs Buckton & Co., Leeds.

Table 1 - Tension Tests on Wire.

Material.	Wire Diameter. (Ins.)	S.W.G.	Elastic Limit (Tons/ sq.in.)	Maximum Stress (Tons/ sq.in.)	Reduction of Area. %	E
Hard drawn	0.152	8	52.16	93.08	37.23	-
Steel Wire	0.127	10	46.10	103.1	32.98	-
(0.83% C.)	0.109	11-12	Indeterminate	100.0	39.63	-

Note.- In Table 1, the limits of proportionality or true elastic limit were, in many cases, quite indeterminate from the stress-strain curves.

Table 2 /

Table 2 - Torsion Tests on Wire.

...terial.	Wire Diameter. (Ins.)	S.W.G.	Max. Twist in 1-inch Length.	Maximum Stress (Tons/ sq.in.)	Modulus ($N \times 10^6$) lb./sq. in.	Fracture.
...rd drawn	0.152	8	1134°	78.1	9.53	Shear
...eel wire	0.127	10	1346°	89.3	11.00	Shear
...0.83% C.)	0.109	11-12	1189°	87.8	8.34	Shear

STATIC COMPRESSION TESTS ON SPRINGS.

The compression tests on the springs were carried out on the same "Olsen" machine. By employing the small beam jockey weight, the full scale reading is 1,000 lb., so that very accurate results can be obtained. The load may be increased by increments of 1/4 lb.

It was found that after about 30 per cent of the maximum load required to compress the specimen hard up (i.e., the "closing load") had been applied, the end coils began to close up, thus shortening the effective length of the spring. The load-compression curves indicate this by a decided change of slope. With additional loads the curves resume their original slopes, only to change them again when between 50 per cent and 60 per cent of the closing load had been applied. This is no doubt due to the next coils closing up with the first ones. At about 80 per cent of the closing load the slopes of the curves in general become very much steeper, Series 4(a) giving noticeable examples of this. Curves approximating very closely to the straight line are those of Series 6.

(Representative curves at end of thesis - Figs.1-7).

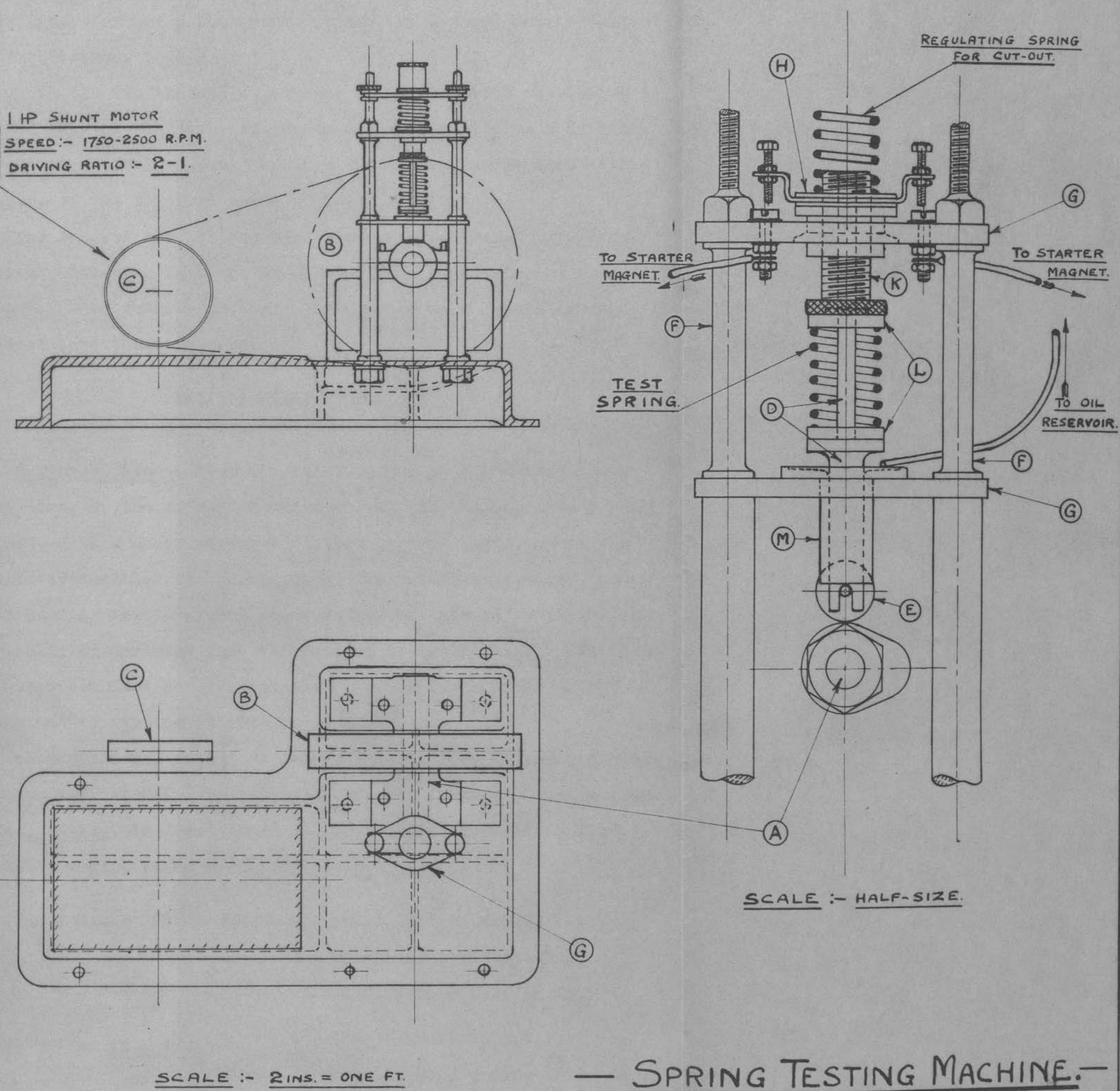
APPARATUS /

APPARATUS FOR FATIGUE TESTING (Fig.8 overleaf).

The apparatus used for the fatigue tests was designed so as to give a movement to the springs as similar as possible to that obtaining under working conditions. The machine consists essentially of a camshaft, A, carrying a combined pulley and flywheel, B, driven by an electric motor, C, and running in two plain cast-iron bearings of large dimensions on a heavy foundation base. The drive as originally designed occasioned some little trouble, as, owing to its shortness, the leather belt used was continually slipping and pulling through the buckle. This was obviated by employing a composite rubber and canvas belt. However, as it was impossible to keep the belt free from oil, which caused rapid deterioration of the material, a leather belt, ready lace-jointed by the manufacturer, was tried. This belt has given excellent service throughout.

The tappet rod, D, which also takes the place of the valve, is fitted with a roller, E, and is supported by a couple of steel columns, F, connected by diamond-shaped bridge pieces, G, which carry the bushes. In the upper bridge piece a special automatic stop device, H, is situated. The top bush, K, incorporates an adjustable collar, by means of which the load on the spring may be altered. This load is fixed by calipering the length of the spring in position in the collars, L, before the test begins. Lubrication of the tappet and roller is effected by means of an oil pipe leading from a reservoir placed on top of the machine and discharging into the cupped top of the bottom bush, M.

The equipment of the machine includes a speed indicator, a "Veeder" counter, registering up to 10,000,000 revolutions, coarse and fine rheostats for accurate speed adjustments, and an Elverson oscilloscope. This latter instrument enables the behaviour of the spring at any point in the cam revolution to be observed at any /



— SPRING TESTING MACHINE. —

— GENERAL ARRANGT. & DETAILS. —

FIG. 8.

any speed of the machine. The spring may either be observed as "stationary" at any point in the stroke, or a "slow motion" effect may be obtained.

With the two rheostats referred to, exact speed regulation is limited only by the scale of the speed indicator. Each division is equivalent to 10 r.p.m., so that the spring can be kept within 5 r.p.m. of the required speed.

The tappets and rollers used are scrapped "Wasp" type engine material, obtained from the Royal Aircraft Establishment, Farnborough. The rods which carry the springs were specially made to screw into these tappets.

FATIGUE TEST FORMULAE.

Stresses, etc.- When a helical spring is subjected to any axial load, W, the effect on the wire is a torque, and the stress, f, induced is a shear stress. In the present tests, where the load is transmitted to the spring by the rotation of a cam, unknown bending and torsional stresses may be induced, owing to the difficulty of ensuring that the loading is truly axial. Particular attention must be given to the grinding of the ends of the spring and to fitting it into the machine.

As regards the method of stress calculation, it was considered to be sufficiently accurate to treat the springs as being close-coiled, (i.e., sin α and tan α in the formula are neglected, "α", the helix angle, being small).

Then $W R = f \frac{\pi d^3}{16}$ where W = Axial load on spring (lb.)

R = Radius of helix (inches)

$\therefore f = \frac{16 W R}{\pi d^3}$ f = shear stress (lb./sq.in.)

d = dia. of wire (ins.)

$= \frac{16 W D/2}{\pi d^3}$ since R = D/2, where D = mean coil dia. (ins.)

i.e., Shear Stress (f) $= \frac{8 W D}{\pi d^3}$ lb./sq.in.

$$= \frac{W D}{280 \pi d^3} \text{ tons/sq.in.}$$

Having decided on the maximum load at which the test is to be run, the corresponding stress can be calculated. The length of the spring for this load may then be determined, either by direct measurement on the Olsen machine, or by interpolation on the load-compression curve. Likewise, having fixed the cam-lift for the required range of stress, the extended length of the spring is known, and hence the corresponding minimum load can be determined, and the minimum stress calculated.

<u>Modulus of Rigidity</u>.- The Modulus of Rigidity for each spring under test conditions was calculated from the usual formula, viz.:-

$$\text{Modulus of Rigidity (N)} = \frac{8\,W\,D^3\,n}{d^4\,\delta}\ \text{lb./sq.in.}$$

where W = axial load on spring (lb.)

D = mean coil dia. of spring (ins.)

n = number of effective coils

$$= \frac{\text{Effective length for test load (ins.)}}{\text{Pitch of coils for test load (ins.)}}$$

d = wire dia. (ins.)

δ = deflection under load W (ins.)

Then $\frac{W}{\delta}$ = "Rate" of spring (i.e., load/inch deflection), and may be determined from the slope of the load-compression curve.

<u>Frequency</u>.- The frequency of any spring under test conditions may be calculated from the formula:-

$$\text{Frequency} = \frac{62.4\,d\,p\sqrt{N}}{R^2\,\ell}\ \text{vibrations/min.}$$

where d = wire dia. (ins.)

p = pitch of coils for test load (ins.)

N = modulus of rigidity (lb./sq.in.)

R = radius of helix (ins.)

ℓ = effective length of spring for test load(ins.)

Then R = D/2, where D = mean coil dia. (ins.) and $R^2 = D^2/4$.

$$\therefore\ \text{Frequency} = \frac{249.6\,d\,p\sqrt{N}}{D^2\,\ell}\ \text{vibrations/min.}$$

FATIGUE TESTS.

Description.- Complete details of the earlier fatigue tests are given in Tables 4 and 4(a) at end of thesis. The duration of the tests varied from 5 to 10 days continuous running, corresponding to 6-12 million revolutions of the cam shaft. At the end of each test the spring was measured for "creep", and then compressed hard up to determine the decrease in the closing load.

After one month from the completion of each test the spring was again compressed hard up, but, in every case, the closing load was found to be practically as before. No exact results could be obtained, as the Olsen machine, in which the springs were compressed, was not sensitive enough to read to more than about 2 or 3 pounds. The amount of "creep" in the spring is permanent.

The majority of the specimens were tested previous to the arrival of the Elverson oscilloscope, so that the behaviour of these springs could not be very closely observed.

The first spring to be observed by the oscilloscope was Series 27, Test Piece 3. This spring was run at a speed of 1050 r.p.m., at which speed no actual surging was observed. The number of vibrations per revolution of the cam shaft at this speed was seven (7) and the frequency therefore was 7350.

The initial load on the spring (about 90 per cent of the closing load) was 52.13 lb. With this load no "bounce" could be observed, the roller remaining on the cam throughout the cycle.

(Note.- "Bounce" in general refers to failure of contact between roller and cam at some point of the revolution of the latter. More particularly, to failure of the roller to maintain contact as it passes over the crest of the cam, due to the spring being too weak, or insufficiently compressed, to synchronise its action with that of the cam at the speed of revolution.)

Continuing the test, the load was then reduced to 45 lb., no "bounce" being observed. The number of vibrations of the spring per revolution was nine (9), with a frequency of 9450.

Further reducing the load to 40 lb. resulted in a very slight bounce at the crest. The number of vibrations was now eight (8) and the frequency 8000.

At a load of 35 lb. the vibrations were small and many, and it was impossible to count them accurately. The bounce was again hardly noticeable.

At 30 lb. the vibrations were 7 per revolution with fairly large amplitudes. Bouncing was slightly more noticeable at the crest of the cam.

The load was now reduced to $18\frac{1}{2}$ lb., when bouncing was clearly visible.

With all these loads no actual surging was observed.

The spring was run for $12\frac{1}{2}$ million revolutions, corresponding to 198 hours' running time. At the end of that time the spring had shortened by 0.103 inch, but the closing load had not materially altered.

Outer Exhaust Valve Spring of 450 H.P. Napier Lion.

In a preliminary run it was observed that this spring had a synchronous speed at 958 r.p.m. Accordingly the machine was kept at this speed throughout the test. The initial load on the spring was 48.6 lb., corresponding to a torsional stress of 32.6 tons per sq. inch.

The number of vibrations per revolution of the cam-shaft was nine (9), with a frequency of 8622. The amplitude of vibrations as measured by eye was about 0.125 inch.

After /

After running for 200 hours at this speed without any sign of fatigue, the spring was taken out and compressed hard up, when the closing load was found to be 46 lb. instead of the original 54 lb. The overall length of the spring, however, had shortened by only 0.008 inch.

Contact between cam and roller was perfect throughout.

It will be seen from Table 4(a) that no fractures were obtained, even after running a spring at a synchronous speed for nearly 12 million revolutions.

To find out if any appreciable difference could be observed between the springs made of hard drawn wire, and springs such as are used in aero engines, a few of the latter were obtained from the Supermarine Aviation Co., Southampton, who supplied the following:-

1 set of 4 springs from 450 H.P. Napier "Lion" Engine.

1 " " " " 240 H.P. Siddeley "Puma" Engine.

Details of two tests on Napier "Lion" springs are given in Tables 4 and 4(a). These tests reveal no practical difference between the two types of springs, an observation which also applies to a test of an ordinary motor-car valve spring. "Creep" of the springs under load is very much less in the case of the aero engine, and motor car valve springs, presumably due to the latter being tempered after coiling.

FURTHER /

FURTHER FATIGUE TESTS.

Consideration of these earlier tests suggested two further lines of investigation, viz.:-

1. To increase the duration of the ordinary fatigue tests up to the now recognised 10^7 reversals basis.

2. To heat the springs to temperatures up to 200° C. while under test.

The electric heater which had been made was found unsatisfactory in use, so a new design was put in hand, and in the meantime the ordinary fatigue tests were proceeded with, as indicated.

The stiffest springs available, and, therefore, giving the highest range of stress, were those of Series 6. Accordingly a start was made on Test Piece 3 of this Series, Test Pieces 1 and 2 having already been tested, but only up to less than 8 million reversals (see Tables 4 and 4(a)).

Series 6 - Test Piece 3.

Set to run at a maximum test load of 145 lb. (closing load 150 lb.), the corresponding maximum stress was 39.04 tons/sq.in. A cam-lift of 3/8" gave a range of stress of 14.0 tons/sq.in., the mean stress being 32.04 tons/sq.in.

When about 12 million reversals had been endured, the spring was observed to be deformed. Complete failure occurred at 12.35 million reversals (210 hours), the spring cracking in two places in the top coils.

Modulus of Rigidity = 10.05×10^6 lb./sq.in.

Series 6 - Test Piece 4.

In order to verify this result, a fresh test was commenced with a specimen from the same series, to give approximately similar conditions of loading to Test Piece 3.

The /

The maximum test load was 146 lb. (closing load 148 lb.), the corresponding maximum stress being 39.41 tons/sq.in., and the range of stress and mean stress were 14.05 tons/sq.in. and 32.39 tons/sq.in. respectively.

In this case deformation became apparent at an earlier stage (at about $9\frac{1}{4}$ million as against about 12 million previously). Complete failure occurred at 10.83 million reversals (164 hrs.), the spring cracking in one place only in the <u>top</u> coils.

Modulus of Rigidity = 9.85×10^6 lb./sq.in.

<u>Series 9 - Test Piece 2.</u>

There was no visible weakening of this specimen after more than 17 million reversals (263 hrs). With a maximum test load of 147 lb. (closing load 150 lb.), the maximum stress was 39.17 tons/sq.in., range of stress 13.06 tons/sq.in., and mean stress 32.64 tons/sq.in. The spring had shortened by 0.108" ("creep"), and the closing load had decreased by 10 lb.

Differs materially from Series 6 only in respect of having an extra coil, hence giving lower range of stress for same cam-lift.

Modulus of Rigidity = 9.80×10^6 lb./sq.in.

<u>Series 3 - Test Piece 1.</u>

Deformation became apparent at little more than 2 million reversals, and complete failure occurred at 2.597 million reversals ($39\frac{1}{2}$ hrs.), the spring cracking in two places in the <u>centre</u> coils.

With a maximum test load of 147 lb. (closing load 150 lb.) the maximum stress was 40.4 tons/sq.in. Range of stress, 19.80 tons/sq.in., and mean stress 30.50 tons/sq.in.

Modulus of Rigidity = 10.57×10^6 lb./sq.in.

<u>Note</u>.- Each of the above specimens was observed at frequent intervals with the oscilloscope, and at no time was any "bouncing" or "surging" apparent. Cam and roller contact was perfect in each case. There was no evidence of any oscillation whatever of the coils of these springs during a cam-shaft revolution, at the speeds of the respective tests.

<u>Series 6</u> /

Series 6 - Test Piece 5.

This specimen endured 12.5 million reversals (190 hrs.) without any visible evidence of fatigue; but there were frequent periods of rest, owing to involuntary stoppages of the machine.

The maximum test load was 141 lb. (closing load 143 lb.), giving a maximum stress of 38.21 tons/sq.in., and a range of stress of 13.82 tons/sq.in., with a cam-lift of 5/16". This test is not included in the tabulated results.

There being no other specimens of Series 3 available, it was decided to test further specimens of Series 6 at ranges of stress of the order of 19 tons/sq.in.

For this purpose a new cam, similar to those already in use, but of 1/2" lift, was obtained.

Series 6 - Test Piece 6.

Complete failure occurred at 5.33 million reversals (88 hrs.), being about 1.2 million reversals from first appearance of deformation.

At a maximum stress of 40.29 tons/sq.in., the range of stress was 18.66 tons/sq.in., and the mean stress 30.96 tons/sq.in.

There were three cracks in this spring, the first appearing in the bottom coil, with two others developing in alternate coils above it.

Modulus of Rigidity = 9.94×10^6 lb./sq.in.

Series 6 - Test Piece 7.

Complete failure occurred at 10.47 million reversals (174 hrs), the spring cracking in one place in the top coils.

At a maximum stress of 39.07 tons/sq.in., the range of stress was 18.43 tons/sq.in., and the mean stress 29.86 tons/sq.in.

Modulus of Rigidity = 10.24×10^6 lb./sq.in.

Series 6 /

Series 6 - Test Piece 8.

Complete failure occurred at 5.308 million reversals ($80\frac{1}{2}$ hrs), being about 1.1 million from first appearance of deformation.

At a maximum stress of 40.76 tons/sq.in., the range of stress was 19.31 tons/sq.in., and the mean stress 31.10 tons/sq.in.

This spring cracked in four places in adjacent coils, starting from the bottom.

Modulus of Rigidity = 10.08×10^6 lb./sq.in.

Series 6 - Test Piece 9.

Found broken in four places in the bottom coils after only 0.823 million reversals ($10\frac{1}{2}$ hrs). Set to run at 1100 r.p.m., the handle of the regulating resistance had moved in some way, causing the speed to rise to 1300 r.p.m. The calculated frequency of the spring indicates the possibility of a certain amount of "surge" at about the latter speed.

The maximum stress was 39.73 tons/sq.in., the range of stress being 18.8 tons/sq.in., and the mean stress 30.33 tons/sq.in.

Modulus of Rigidity = 10.14×10^6 lb./sq.in.

Series 6 - Test Piece 10.

Complete failure occurred at 10.06 million reversals (106 hrs), being about 0.6 million from first appearance of deformation. Broke in four pieces, starting from the top coil, with a fifth crack developing in the centre coil.

The maximum stress was 39.86 tons/sq.in., the range of stress being 18.59 tons/sq.in., and the mean stress 30.57 tons/sq.in.

Modulus of Rigidity = 9.65×10^6 lb./sq.in.

Note.- With the exception of Test Piece 9, these springs were observed with the oscilloscope. In no case was there any apparent oscillation of the coils. As regards "bouncing", in every case cam and roller contact was perfect throughout.

Modulus of Rigidity	(Maximum	= 10.24×10^6 lb./sq.in.
	(Minimum	= 9.65×10^6 " " "
	(Mean	= 10.00×10^6 " " " (nearly)

No further specimens of this series were available. (For complete details of these tests, see Tables 5 and 5(a)).

The following tests were carried out in order to discover if fractures could be obtained with other springs which could be similarly stressed to those of Series 6.

<u>Series 12 - Test Piece 1.</u>

Endured 14.12 million reversals (230 hrs.) without any visible evidence of fatigue. The spring shortened by 0.082", and the final closing load was 11 lb. less.

At a maximum stress of 41.59 tons/sq.in., the range of stress was 13.63 tons/sq.in., and the mean stress 34.78 tons/sq.in.

Modulus of Rigidity = 9.96×10^6 lb./sq.in.

<u>Series 12 - Test Piece 3.</u>

Endured 12 million reversals (200 hrs.) without any visible evidence of fatigue. The spring shortened by 0.06" and the final closing load was 9 lb. less.

At a maximum stress of 40.27 tons/sq.in., the range of stress was 18.53 tons/sq.in., and the mean stress 31.0 tons/sq.in.

Modulus of Rigidity = 10.02×10^6 lb./sq.in.

<u>Series 15 - Test Piece 3.</u>

Endured 12.16 million reversals (156 hrs.) without any visible evidence of fatigue. The spring shortened by 0.062" and the final closing load was 10 lb. less.

At a maximum stress of 31.67 tons/sq.in., the range of stress was 10.22 tons/sq.in., and the mean stress 26.56 tons/sq.in.

Modulus of Rigidity = 11.0×10^6 lb./sq.in.

(For complete details of these three tests, see Tables 5 and 5(a)).

So /

So far all tests have been made on springs of No.8 S.W.G. The following tests are on springs of No.11-12 S.W.G. (Series 1) and No.10 S.W.G. (Series 2).

Series 1 - Test Piece 1.

Endured 15.4 million reversals (234 hrs.) without any visible evidence of fatigue. The spring shortened by 0.025" and the final closing load was 7 lb. less.

At a maximum stress of 41.16 tons/sq.in., the range of stress was 13.0 tons/sq.in., and the mean stress 34.66 tons/sq.inch.

Modulus of Rigidity = 11.30 x 10^6 lb./sq.in.

Series 1 - Test Piece 2.

Endured 14.78 million reversals (224 hrs) without any visible evidence of fatigue. The spring shortened by 0.032" and the final closing load was 8 lb. less.

At a maximum stress of 42.98 tons/sq.in., the range of stress was 16.12 tons/sq.in., and the mean stress 34.92 tons/sq.in.

Modulus of Rigidity = 10.63 x 10^6 lb./sq.in.

Series 2 - Test Piece 1.

Endured 12.23 million reversals (186 hrs.) without any visible evidence of fatigue. The spring shortened by 0.067", and the final closing load was 6 lb. less.

At a maximum stress of 43.16 tons/sq.in., the range of stress was 14.57 tons/sq.in., and the mean stress 35.88 tons/sq.in.

Modulus of Rigidity = 10.16 x 10^6 lb./sq.in.

Series 2 /

Series 2 - Test Piece 3.

Complete failure occurred at 10.86 million reversals (167 hrs.) being about 1.1 million from first appearance of deformation. This spring cracked in one place only in the top coils.

At a maximum stress of 40.54 tons/sq.in., the range of stress was 17.45 tons/sq.in., and the mean stress 31.82 tons/sq.in.

At the test speed (1100 r.p.m.), slight oscillation of the coils was apparent.

Modulus of Rigidity = 10.24×10^6 lb./sq.in.

In preliminary tests with the electric heater, which was now ready for use, a Napier "Lion" exhaust valve spring ran for over 48 hours at a temperature of 300° C., without any injurious effect being apparent. There was no "creep" of the spring whatever.

On the other hand, "creep" was found to be excessive in the case of the hard-drawn springs. The following test of a hard-drawn spring was run at the lowest temperature which could be obtained with the heater, viz., 135° C.

Series 2 - Test Piece 2.

(Tested 135° C.)

Endured 12.81 million reversals (164 hrs.) without any visible evidence of fatigue. The "creep" was excessive, being finally 0.30 inch; but a compression test of the spring immediately after the fatigue test gave a closing load of 80 lb., this being equal to the original value. Latterly, when the spring was quite cold, the closing load was found to be only 70 lb.

At a maximum stress of 44.53 tons/sq.in., the range of stress was 16.34 tons/sq.in., and the mean stress 36.36 tons/sq.in.

Modulus of Rigidity = 9.99×10^6 lb./sq.in.

(For complete details of above tests, see Tables 9 and 9(a)).

ELECTRIC HEATER FOR TEMPERATURE TESTS (Fig. overleaf.)

This apparatus was designed so that, if desired, any spring under test might be maintained at a constant elevated temperature throughout that test.

Referring to the diagram overleaf, the heaters, A, which are formed of Nickel Chrome wires, are embedded in the surface of porous insulating brick, B, so that the maximum possible heat insulation may be obtained in the small space available. This in order that there may be sufficient uniformity of temperature distribution in the chamber to give a thermometer reading as nearly true to the actual heat temperature of the spring under test as possible.

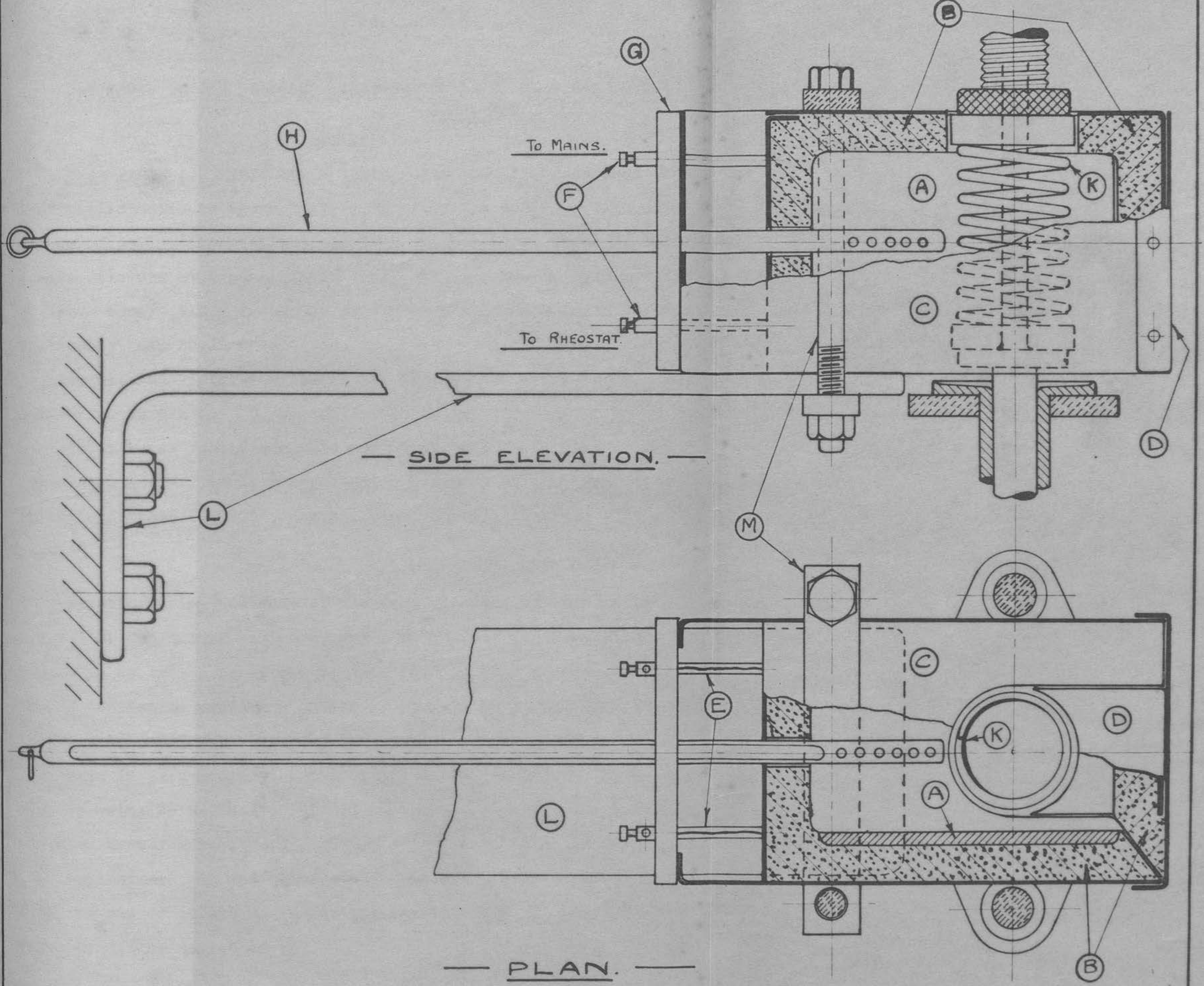
The porous insulating brick is contained in a sheet steel casing, C, which is fitted with a removable end cover, D, also brick-lined. This arrangement enables the apparatus to be fitted to the testing machine after the spring has been adjusted in position.

The ends of the heater wires are carried through glass insulators, E, to the four terminals, F, situated on the facing, G, which is carried on extensions of two sides of the steel casing. Temperatures are registered by a Cambridge armoured thermometer, H, which is introduced into the hot space as shown in the figure. A spring, K, is shown in position in the heater, the upper opening in which may be sealed with asbestos washers and twine to prevent through draughts.

The whole apparatus is supported on an angle-bar, L, and is held in position by a clamp, M.

With this heater the temperature range was up to 550° C. and by the introduction of suitable resistances into the heater circuit any required temperature between this maximum, and normal temperatures, could have been maintained.

As noted on the previous page with regard to the test of Test Piece 2 of Series 2, the resistance available at that time (100 ohms; 1.25 amps.) could only control the temperatures from 135° C. upwards.



— ELECTRIC HEATER. —

SCALE :- 8 INS. = ONE FT.

The range of the Cambridge thermometer is 0° C. - 540° C.

Series 12(a).

Test Piece 1.- This was a spring of Series 12, shortened from 5 effective coils to approximately 3½ effective coils. With this number of coils, almost identical test conditions to those of Series 6 were obtained at a cam-lift of 3/8", viz.:- At a maximum stress of 39.43 tons/sq.in., the range of stress was 18.45 tons/sq.in. and the mean stress 30.21 tons/sq.in.

Modulus of Rigidity = 11.0×10^6 lb./sq.in., as compared with mean value 10.0×10^6 lb./sq.in. for Series 6.

Under these conditions this spring endured 11.89 million reversals (180 hrs.) without any visible evidence of fatigue. The spring shortened by 0.02", and the final closing load was 3 lb. less.

As this spring was made of the same diameter of wire (No.8 S.W.G.) as springs of Series 6, which failed within 11 million reversals at ranges of stress of from 14.0 to 19.3 tons/sq.in., it was decided to prepare a number of springs of Series 12 (a) in order to run further comparative tests.

This in preference to continuing the heat tests, so unsatisfactory owing to excessive "creep" of the hard-drawn springs at elevated temperatures.

Furthermore, it was calculated that, using the cam of 1/2" lift, ranges of stress up to 26 tons/sq.in. could be obtained with springs of Series 12 (a).

Test Piece 2.- Complete failure occurred at 0.73 million reversals (11 hrs.), the spring cracking in two places in the top coils. The primary crack developed into a particularly ragged tear; but the secondary crack was of the nature of a clean break, rather than of the usual cracking and tearing. A previously similar case was that of Test Piece 9 (Series 6).

The /

The range of stress was particularly high, being 26.53 tons/sq. in., with a maximum stress of 41.75 tons/sq.in., and a mean stress of 28.99 tons/sq.in.

Modulus of Rigidity = 10.75×10^6 lb./sq.in.

<u>Test Piece 3</u>.- Complete failure occurred at 3.08 million reversals (47 hrs.), the spring cracking in one place in the <u>bottom</u> coil.

At a maximum stress of 39.07 tons/sq.in., the range of stress was 25.21 tons/sq.in., and the mean stress 26.47 tons/sq.in.

Modulus of Rigidity = 10.47×10^6 lb./sq.in.

<u>Test Piece 4</u>.- Complete failure occurred at 0.453 million reversals (7 hrs.), by cracking in one place - in the <u>top</u> coil.

At a maximum stress of 39.7 tons/sq.in., the range of stress was 25.98 tons/sq.in., and the mean stress 26.71 tons/sq.in.

Modulus of Rigidity = 11.5×10^6 lb./sq.in.

<u>Test Piece 5</u>.- Complete failure occurred at 0.53 million reversals (8 hrs), by cracking in one place - in the <u>top</u> coil.

At a maximum stress of 39.78 tons/sq.in., the range of stress was 23.09 tons/sq.in., and the mean stress 28.24 tons/sq.in.

Modulus of Rigidity = 10.47×10^6 lb./sq.in.

<u>Test Piece 6</u>.- Complete failure occurred at 1.99 million reversals (30 hrs.), by cracking in one place - in the <u>top</u> coil.

At a maximum stress of 38.32 tons/sq.in., the range of stress was 21.49 tons/sq.in., and the mean stress 27.58 tons/sq.in.

Modulus of Rigidity = 10.32×10^6 lb./sq.in.

<u>Test Piece 7</u>. Complete failure occurred at 0.556 million reversals (7 hrs.), being about 0.022 million reversals from first appearance of deformation, the spring cracking in one place - in the top coil.

At a maximum stress of 40.71 tons/sq.in., the range of stress was 23.92 tons/sq.in., and the mean stress 28.75 tons/sq.in.

Modulus of Rigidity = 10.5×10^6 lb./sq.in.

Test Piece 8.- Complete failure occurred at 0.668 million reversals ($12\frac{1}{2}$ hrs.) by cracking in three places, two of the fractures occurring only about 1/4 inch apart on the same coil.

At a maximum stress of 40.17 tons/sq.in., the range of stress was 22.74 tons/sq.in., and the mean stress 28.8 tons/sq.in.

Modulus of Rigidity = 10.38×10^6 lb./sq.in.

Test Piece 9.- Complete failure occurred at 3.1 million reversals (47 hrs.), by cracking in one place - in the top coil.

At a maximum stress of 40.07 tons/sq.in., the range of stress was 21.98 tons/sq.in., and the mean stress 29.08 tons/sq.in.

Modulus of Rigidity = 10.58×10^6 lb./sq.in.

Test Piece 10.- Complete failure occurred at 1.08 million reversals ($16\frac{1}{2}$ hrs.), being about 0.105 million reversals from first appearance of deformation, the spring cracking in one place - in the top coil.

At a maximum stress of 30.0 tons/sq.in., the range of stress was 21.1 tons/sq.in., and the mean stress 19.5 tons/sq.in.

Modulus of Rigidity = 10.84×10^6 lb./sq.in.

It will be observed that this spring failed after enduring only about one-third the number of reversals which caused failure in the case of Test Piece 9. In the latter case, not only was the mean stress much greater (by about 10 tons/sq.in.), but the range of stress was also slightly higher (by 0.88 tons/sq.in.)

Test Piece 11.- Complete failure occurred after 4.40 million reversals (61 hrs.), by bracking in one place - in the top coil.

This spring was tested at the minimum loading consistent with perfect adhesion between cam and roller - i.e., the mean stress was the minimum possible for satisfactory working.

At a maximum stress of 24.95 tons/sq.in., the range of stress was 21.40 tons/sq.in., and the mean stress 14.25 tons/sq.in.

Modulus of Rigidity = 10.42×10^6 lb./sq.in.

Test Piece 12.- Endured 11.30 million reversals (145 hrs.), without any visible evidence of fatigue. The spring shortened by 0.03" and the final closing load was 5 lb. less.

At a maximum stress of 40.04 tons/sq.in., the range of stress was 19.85 tons/sq.in., and the mean stress 30.12 tons/sq.in.

Modulus of Rigidity = 10.16×10^6 lb./sq.in.

Test Piece 13.- Complete failure occurred after from 2.0 to 2.5 million reversals (26-32 hrs.), by cracking in two places in the centre coils. (The exact number of reversals to fracture is unknown, owing to the automatic stop failing to operate).

At a maximum stress of 41.52 tons/sq.in., the range of stress was 21.82 tons/sq.in., and the mean stress 30.61 tons/sq.in.

Modulus of Rigidity = 10.56×10^6 lb./sq.in.

Although not all of these springs were observed with the oscilloscope, owing to the latter being out of order for some time - the trouble was finally traced to a defect in the lamp cable, which was replaced - there was no apparent oscillation of the coils in the case of those specimens which were observed.

Furthermore, calculation of synchronous speeds for each spring shows that the case in which "surging" effect would be most probable is that of Test Piece 3; and, in a lesser degree, Test Pieces 6, 8, and 10. Referring to the endurance curve for this series (Fig.9), the only case of premature failure possibly due to "surging" effect is that of Test Piece 10. On the other hand, Test Piece 3 will be seen to have run some 2½ million reversals (about 38 hrs.) longer than the range of stress endured would indicate as probable. Test Pieces 6 and 8 conform very closely to the presumed endurance curve.

Other cases, in which the endurance was exceptional in relation to the range of stress, are those of Test Pieces 9 and 11, and, in a lesser degree, Test Piece 2.

Assuming /

Assuming the mean stress of the cycle to have a certain effect on the life of the spring, this might explain the exceptional endurance of Test Piece 11, which has already been referred to as having been tested at the lowest value of the mean stress possible. However this is rather discounted by the fact that in the cases of Test Pieces 2 and 9 the mean stress was particularly high; nor does it explain the endurance of Test Piece 3, where the mean stress was not much below the average value for the Series.

	(Maximum = 30.61 tons/sq.in.	(Test Piece 13)
Mean Stresses	(Minimum = 26.47 tons/sq.in.	(Test Piece 3)
	(Average = 28.7 tons/sq.in. nearly.	

Not included are:- Test Piece 10 (19.50 tons/sq.in.)
" " 11 (14.25 " " ")

As regards the Modulus of Rigidity, this is fairly consistent over the Series:-

Modulus of	(Maximum = 11.50×10^6 lb./sq.in.	(Test Piece No.4)
	(Minimum = 10.16×10^6 " " "	" " No.12)
Rigidity (N)	(Average = 10.61×10^6 " " "	

No more specimens of this Series were available, otherwise further tests would have been made in an endeavour to establish the form of the endurance curve more definitely. The results do not permit of a satisfactory plotting of log S / log N.

Complete details of these tests are given in Tables 6 and 6(a) at end of thesis.

Series 4(a) /

Series 4(a).

Test Piece 1.- This was a spring of Series 4 shortened from 7 effective coils to approximately $4\frac{1}{2}$ effective coils. Very similar to Series 1 (5 effective coils), but permitting of a higher range of stress being obtained.

Complete failure of this specimen occurred after 7 million reversals (106 hrs.), being about 0.03 million reversals from the first appearance of deformation, the spring cracking in one place - in the top coil.

At a maximum stress of 37.63 tons/sq.in., the range of stress was 20.53 tons/sq.in., and the mean stress 27.37 tons/sq.in.

Modulus of Rigidity = 10.78 x 10^6 lb./sq.in.

This preliminary test having yielded a fracture, a set of specimens of this Series was now prepared, and the following tests carried out:-

Test Piece 2.- Complete failure occurred after 1.3 million reversals ($19\frac{3}{4}$ hrs.), by cracking in one place - in the top coil.

At a maximum stress of 37.63 tons/sq.in., the range of stress was 23.75 tons/sq.in., and the mean stress 25.75 tons/sq.in.

Modulus of Rigidity = 10.94 x 10^6 lb./sq.in.

Test Piece 3.- Complete failure occurred after 1.0 million reversals (15 hrs.), by cracking in one place - in the top coil.

At a maximum stress of 38.57 tons/sq.in., the range of stress was 22.28 tons/sq.in., and the mean stress 27.43 tons/sq.in.

Modulus of Rigidity = 10.40 x 10^6 lb./sq.in.

Test Piece 4.- Complete failure occurred after 1.516 million reversals (23 hrs.), by cracking in one place - in the bottom coil.

At a maximum stress of 36.26 tons/sq.in., the range of stress was 21.58 tons/sq.in., and the mean stress 25.47 tons/sq.in.

Modulus of Rigidity = 10.40 x 10^6 lb./sq.in.

Test Piece 5.- /

Test Piece 5.- Complete failure occurred after 1.445 million reversals (22 hrs.), by cracking in one place - in the top coil.

At a maximum stress of 36.97 tons/sq.in., the range of stress was 22.36 tons/sq.in., and the mean stress 25.79 tons/sq.in.

Modulus of Rigidity = 10.46×10^6 lb./sq.in.

Test Piece 6.- This test could not be completed and is not included in the tabulated results.

At a maximum stress of 35.25 tons/sq.in., the range of stress was 21.06 tons/sq.in., and the mean stress 24.72 tons/sq.in. At time of stopping, the spring had endured 2.056 million reversals (31 hrs.).

Test Piece 7.- Complete failure occurred after 8.848 million reversals (134 hrs.), being about 0.59 million reversals from the first appearance of deformation, the spring cracking in two places - in the two top coils, the first crack appearing in the topmost coil.

At a maximum stress of 36.02 tons/sq.in., the range of stress was 22.29 tons/sq.in., and the mean stress 24.88 tons/sq.in.

Modulus of Rigidity = 10.39×10^6 lb./sq.in.

Note.- This spring rotated constantly in the collars throughout the test.

Test Piece 8.- Complete failure occurred after 5.445 million reversals ($90\frac{3}{4}$ hrs.), by cracking in one place - in the bottom coil.

At a maximum stress of 35.75 tons/sq.in., the range of stress was 20.79 tons/sq.in., and the mean stress 25.36 tons/sq.in.

The "creep" of this spring after 4.5 million reversals was 0.01 inch (expressed as a stress = 0.41 tons/sq.in.).

Modulus of Rigidity = 10.10×10^6 lb./sq.in.

Test Piece 9.- /

Test Piece 9.- Complete failure occurred after 6.066 million reversals (92 hrs.), by cracking in two places - in the two bottom of these coils, the first crack appearing in the uppermost coil.

At a maximum stress of 36.02 tons/sq.in., the range of stress was 20.58 tons/sq.in., and the mean stress 25.73 tons/sq.in.

Modulus of Rigidity = 9.71 x 10^6 lb./sq.in.

Test Piece 10.- Complete failure occurred after 5.54 million reversals (92½ hrs.), by cracking in one place - in the centre coil.

At a maximum stress of 35.14 tons/sq.in., the range of stress was 21.86 tons/sq.in., and the mean stress 24.21 tons/sq.in.

Modulus of Rigidity = 10.42 x 10^6 lb./sq.in.

Test Piece 11.- Complete failure occurred after 11.81 million reversals (197 hrs.), being about 0.085 million reversals from first appearance of deformation, the spring cracking in one place - in the centre coil.

At a maximum stress of 36.97 tons/sq.in., the range of stress was 20.21 tons/sq.in., and the mean stress 26.87 tons/sq.in.

The "creep" of this spring was measured at the following times:-

At 4 million reversals	=	0.005 inch.
" 7 " "	=	0.015 "
" 10 " "	=	0.015 "

(Final measurement expressed as a stress = 0.58 tons/sq.in.)

Modulus of Rigidity = 10.48 x 10^6 lb./sq.in.

Test Piece 12.- Endured 12.24 million reversals (204 hrs.) without any visible evidence of fatigue. The amount of "creep" was 0.015" (stress equivalent = 0.55 tons/sq.in.), and the final closing load was 5 lb. less.

At a maximum stress of 37.18 tons/sq.in., the range of stress was 20.0 tons/sq.in., and the mean stress 27.18 tons/sq.in.

Modulus of Rigidity = 9.77 x 10^6 lb./sq.in.

<u>Test Piece 13</u>.- Complete failure occurred after 6.49 million reversals (108 hrs.) by cracking in two places - in the coils immediately above and below the (approximately) centre coil.

At a maximum stress of 36.93 tons/sq.in., the range of stress was 21.90 tons/sq.in., and the mean stress 25.98 tons/sq.in.

The "creep" of this spring after 5 million reversals was 0.025" (stress equivalent = 0.87 tons/sq.in.)

Modulus of Rigidity = 10.73×10^6 lb./sq.in.

<u>Test Piece 14</u>.- Complete failure occurred after 1.41 million reversals ($22\frac{1}{2}$ hrs.), by cracking in one place - in the <u>bottom</u> coil.

At a maximum stress of 36.93 tons/sq.in., the range of stress was 21.90 tons/sq.in., and the mean stress 25.98 tons/sq.in.

It will be observed that, although this spring gave similar stresses for the same loading as Test Piece 13, the former endured for 5 million reversals (about 86 hrs.) longer.

Above 40% compressed, these two springs gave exactly similar results; but, from no load up to 40% compressed, there was a certain amount of variation in the load-compression curves, resulting in a slightly higher average "rate" for Test Piece 14 (45 lb./inch compression as against 44 lb./inch compression for Test Piece 13).

The Modulus of Rigidity, therefore, was higher, being = 10.97×10^6 lb./sq.in.

All these springs were observed with the oscilloscope while under test, and in no case was there any apparent oscillation of the coils at the speed of the test.

As regards "bouncing", there was evidence of this beginning to occur at speeds in the neighbourhood of 1150 r.p.m. Test speeds were accordingly limited to 1100 r.p.m., or less, and in every case there was perfect adhesion between roller and cam.

Referring to the endurance curve for the Series (Fig.11), it will be seen that Test Pieces 2, 7, 10 and 13 have endured an exceptional number of reversals in proportion to the range of stress. This /

This applies particularly to Test Piece 7, which normally would be expected to fail after about $1\frac{1}{4}$ million reversals (19 hrs.), but which in fact endured for nearly 9 million reversals (135 hrs.).

It is observed that Test Pieces 7 and 10 were tested at the two lowest values of mean stress found for the Series, but, as in the case of Series 12 (a), this is again rather discounted by the fact of the mean stresses for Test Pieces 2 and 13 being good average values for the Series.

	(Maximum	= 27.43 tons/sq.in. (Test Piece 3)
Mean Stresses	(Minimum	= 24.21 tons/sq.in. (Test Piece 10)
	(Average	= 26.0 tons/sq.in.

The Modulus of Rigidity is again fairly consistent over the Series, viz.,

Modulus of	(Maximum	= 10.97×10^6 lb./sq.in.	(Test Piece 14)
Rigidity	(Minimum	= 9.71×10^6 lb./sq.in.	" " 9)
(N)	(Average	= 10.43×10^6 lb./sq.in.	

The average value for these springs (Wire 11-12 S.W.G.) is slightly lower than for Series 12(a) Springs (Wire 8 S.W.G.).

For the wire itself the values given in Table 2 are:-

Wire 11-12 S.W.G.:- $N = 8.34 \times 10^6$ lb./sq.in.

Wire 8 S.W.G.:- $N = 9.53 \times 10^6$ lb./sq.in.

A curve of log "S"/log "N" has been plotted for this Series (Fig.12).

The Fatigue Range for this Series of springs would appear to lie within the limits $\pm$ 20.0 tons/sq.in. to $\pm$ 20.2 tons/sq.in.

Complete details of these tests are given in Tables 7 and 7(a) at end of thesis.

Returning to the case of the No.8 S.W.G. wire, as in the springs of Series 6 and 12(a), it is peculiar that springs of Series 6 should have failed at ranges of stress as low as $\pm$ 14 tons/sq.in., whereas the fatigue range for Series 12(a) would appear to be at least $\pm$ 19.8 tons/sq.in.

For thw sake of further comparison between springs of this diameter of wire, the following tewts were next proceeded with.

Series 15(a) /

Series 15(a).

Test Piece 1.- This was a spring of Series 15, shortened from 7 effective coils to approximately $4\frac{1}{2}$ effective coils. Differs from springs of Series 12(a) in having one coil more, and in being of slightly smaller coil diameter. The overall lengths are practically the same for both series, owing to the smaller coil pitch of series 15(a); the maximum ranges of stress possible with the latter are accordingly less.

In the case of Test Piece 1, complete failure occurred after 7.73 million reversals (117 hrs.), by cracking in one place - in the bottom coil.

At a maximum stress of 31.75 tons/sq.in., the range of stress was 19.87 tons/sq.in., and the mean stress 21.82 tons/sq.in.

The "creep" of this spring after 6 million reversals was 0.02 inch (stress equivalent = 0.805 tons/sq.in.)

Modulus of Rigidity = 10.73×10^6 lb./sq.in.

Test Piece 2.- Complete failure occurred after only 0.7 million reversals ($9\frac{3}{4}$ hrs.), by cracking in one place - in the bottom coil.

At a maximum stress of 32.58 tons/sq.in., the range of stress was 20.0 tons/sq.in., and the mean stress 22.58 tons/sq.in.

The oscilloscope showed slight oscillation of this spring at the test-speed (1200 r.p.m.); but raising, or lowering, the speed merely tended to make the oscillations more pronounced. The calculated frequency for the spring indicates the probability of synchronism occurring at speeds in the neighbourhood of 1170 r.p.m. and 1230 r.p.m. respectively.

Modulus of Rigidity = 11.61×10^6 lb./sq.in.

Test /

<u>Test Piece 3</u>.- Complete failure did not occur till after 11.71 million reversals (166 hrs.), by cracking in one place - in the <u>centre</u> coil.

At a maximum stress of 32.53 tons/sq.in., the range of stress was 20.16 tons/sq.in., and the mean stress 22.45 tons/sq.in.

The "creep" of this spring was measured at the following times:-

At 6.5	million reversals		=	0.013 inch
" 8.15	"	"	=	0.018 inch
" 9.5	"	"	=	0.020 inch

(Final measurement expressed as a stress = 0.877 tons/sq.in.)

This spring was also observed to be oscillating slightly at the test-speed (1200 r.p.m.), and the calculated frequency indicates a possible synchronous speed about 1205 r.p.m.

The great endurance of this spring is remarkable in the light of the results of the two preceding tests.

Modulus of Rigidity = 11.76 x 10^6 lb./sq.in.

<u>Test Piece 4</u>.- Endured 12.5 million reversals (189½ hrs.), without any visible evidence of fatigue. The final "creep" of the spring was 0.035 inch and the closing load was 6 lb. less.

"Creep" at 9 million reversals = 0.025 inch.

Stress equivalent of final "creep" (0.035 inch) = 1.48 tons/sq.in.

At a maximum stress of 32.2 tons/sq.in., the range of stress was 19.58 tons/sq.in., and the mean stress 22.41 tons/sq.in.

No oscillation of the coils was observed at the test speed (1100 r.p.m.).

Modulus of Rigidity = 11.86 x 10^6 lb./sq.in.

<u>Test Piece 5</u>.- Complete failure occurred after 4.717 million reversals (73 hrs.), by cracking in one place - in the <u>top</u> coil.

At a maximum stress of 33.07 tons/sq.in., the range of stress was 21.07 tons/sq.in., and the mean stress 22.54 tons/sq.in.

"Creep" /

"Creep" after 2.75 million reversals = 0.01" (Stress equivalent = 0.4 tons/sq.in.).

No oscillation of the coils was observed at the test speed (1075 r.p.m.).

Modulus of Rigidity = 11.27×10^6 lb./sq.in.

Test Piece 6.- Complete failure occurred after only 0.448 million reversals (7 hrs.), by cracking in two places - in the bottom and centre coils.

At a maximum stress of 33.29 tons/sq.in., the range of stress was 21.74 tons/sq.in., and the mean stress 22.42 tons/sq.in.

No oscillation of the coils was observed at the test speed (1075 r.p.m.).

Modulus of Rigidity = 11.37×10^6 lb./sq.in.

Test Piece 7.- Complete failure occurred after only 0.838 million reversals (13 hrs.), by cracking in two places - in the top and centre coils.

At a maximum stress of 32.85 tons/sq.in., the range of stress was 20.58 tons/sq.in., and the mean stress 22.56 tons/sq.in.

No oscillation of the coils was observed at the test speed (1075 r.p.m.).

Modulus of Rigidity = 12.12×10^6 lb./sq.in.

Test Piece 8.- Complete failure occurred after 8.196 million reversals (119 hrs.), by cracking in top coil, with a second crack developing in the centre coil.

At a maximum stress of 32.52 tons/sq.in., the range of stress was 19.87 tons/sq.in., and the mean stress 22.54 tons/sq.in.

The "creep" of this spring was measured at the following times:-

At 2.25 million reversals = 0.01 inch
" 3.5 " " = 0.01 inch
" 5.0 " " = 0.01 inch

(Final measurement expressed as a stress = 0.423 tons/sq.in.)

No /

No oscillation of the coils was observed at the test speed (1150 r.p.m.).

The calculated frequency indicated probable synchronism at speeds in the neighbourhood of 1165 r.p.m. and 1220 r.p.m. respectively, and observation with the oscilloscope showed marked oscillation at about 1215 r.p.m., the number of oscillations being 17 or 18.. (Average frequency = 21,260 vibrations per minute).

The calculated value is 18 oscillations at 1220 r.p.m. approximately. (Frequency = 21,960 vibrations per minute).

Between 1215 r.p.m. and the test speed of 1150 r.p.m. (at which speed no oscillation could be observed), there was no other speed at which the oscillations again became marked, after ~~rapidly dying away~~ immediately the speed fell slightly below 1215 r.p.m.

Modulus of Rigidity = 11.26×10^6 lb./sq.in.

Test Piece 9.- Complete failure occurred after 4.786 million reversals ($72\frac{1}{2}$ hrs.), by cracking in the centre coil, with a second crack developing in the bottom coil.

At a maximum stress of 32.59 tons/sq.in., the range of stress was 20.28 tons/sq.in., and the mean stress 22.45 tons/sq.in.

The "creep" of this spring was measured at the following times:-

At 1.5 million reversals = 0.02 inch.

" 3.0 " " = 0.02 inch.

(Final measurement expressed as a stress = 0.797 tons/sq.in.)

No oscillation of the coils was observed at the test speed (1100 r.p.m.); but there was a certain amount of oscillation between the limits 1150-1250 r.p.m. The calculated frequency indicated probable synchronism at speeds in the neighbourhood of 1110 r.p.m., 1170 r.p.m. and 1240 r.p.m.

Modulus of Rigidity = 11.40×10^6 lb./sq.in.

Test /

Test Piece 10.- Endured 12.5 million reversals (194 hrs.) without any visible evidence of fatigue. The final "creep" of the spring was 0.022" and the closing load was 4 lb. less.

"Creep" at 6 million reversals = 0.022".

Stress equivalent of final "creep" (0.022") = 0.921 tons/sq. in.

At a maximum stress of 32.92 tons/sq.in., the range of stress was 19.33 tons/sq.in., and the mean stress 23.25 tons/sq.in.

No oscillation of the coils was observed at the test speed (1075 r.p.m.); but at the following approximate speeds oscillation was fairly pronounced:- 950, 1000, 1050, 1100, 1150 and 1280 r.p.m. respectively. The number of oscillations per revolution at above speeds could not be accurately counted.

The calculated frequency gives the following probable synchronous speeds and corresponding vibrations per revolution of the coils:-

958 r.p.m.	-	23 oscillations	per	revolution	
1002 "	-	22 "	"	"	
1050 "	-	21 "	"	"	
1102 "	-	20 "	"	"	
1160 "	-	19 "	"	"	
1224 "	-	18 "	"	"	
1300 "	-	17 "	"	"	

The observed speeds are in good agreement with these values, except in the case of the speed of 1224 r.p.m., at which practically no oscillation was observed. There is also some discrepancy between the observed speed of 1280 r.p.m. and the calculated value of 1300 r.p.m.

Modulus of Rigidity = 11.41 x 10^6 lb./sq.in.

Test /

<u>Test Piece 11</u>.- Complete failure occurred after 7.96 million reversals (106 hrs.), by cracking in one place in the <u>centre</u> coil.

At a maximum stress of 32.94 tons/sq.in., the range of stress was 20.9 tons/sq.in., and the mean stress 22.49 tons/sq.in.

"Creep" at 5.75 million reversals = 0.014 inch (Stress equivalent = 0.58 tons/sq.in.).

There was no oscillation of the coils at the test speed (1250 r.p.m.); but at certain lower speeds, viz., 1070, 1120 and 1180 r.p.m. oscillation was fairly pronounced, particularly at 1120 r.p.m. The calculated speeds are not in very good agreement, viz.:-

1088	r.p.m.	- 20	vibrations per revolution
1146	"	- 19	" " "
1209	"	- 18	" " "

Modulus of Rigidity = 11.9×10^6 lb./sq.in.

Throughout these tests there was perfect adhesion between roller and cam (<u>i.e.</u>, there was no "bouncing" whatever).

An endurance curve has been plotted (Fig.10), which indicates Test Pieces 3, 5, and 9 as having endured an exceptional number of reversals. The only case of premature failure is that of Test Piece 2, this result being probably due to the "surging" effect which was observed to be present at the test-speed.

As slight oscillation was also observed in the case of Test Piece 3, the lengthy endurance of this specimen is all the more inexplicable.

For this Series of springs an endeavour was made to keep the values of the mean stress in as close agreement as possible; but a certain amount of variation, particularly in the case of Test Pieces 1 and 10, could not be avoided.

Mean Stresses (Maximum = 23.25 tons/sq.in. (Test Piece 10)
(Minimum = 21.82 tons/sq.in. (Test Piece 1)
(Average = 22.5 tons/sq.in. (nearly).

The /

The Moduli of Rigidity are appreciably higher than for Series 6 and 12(a), viz.:-

Modulus of Rigidity (N) (Maximum = 12.12×10^6 lb./sq.in. (Test Piece 7)
(Minimum = 10.73×10^6 lb./sq.in. (Test Piece 1)
(Average = 11.56×10^6 lb./sq.in.

The Fatigue Range for this Series would appear to lie within the limits ± 19.6 tons/sq.in. to ± 19.8 tons/sq.in., as compared with something like ± 20.5 tons/sq.in. to ± 20.9 tons/sq.in. for Series 12(a). Considered in conjunction with the results obtained from Series 6, it would seem that the coiling of this fairly large diameter wire (No.8 S.W.G.) into a helix of small radius produces defects in the material which result in a lowering of the Fatigue Range. This will be apparent from the following tabulation:-

B = Broken Spring. U = Unbroken Spring.

Series No.	S.W.G.	Coil Dia. (Ins.)	Range of Stress (Tons/sq.inch)	Reversals (Millions)	Test Piece No.
6	8	1.130	14.00	12.35 (B)	3
		1.132	14.05	10.83 (B)	4
15(a)	8	1.390	19.58	12.50 (U)	4
		1.387	19.87	8.196 (B)	8
12(a)	8	1.412	19.85	11.30 (U)	12
		1.419	21.40	4.40 (B)	11

It was hoped to investigate this matter further by carrying out some tests on springs of an average coil diameter of 1.64 inches. However, in proceeding in this direction, it was found impossible to obtain sufficiently high ranges of stress with these springs.

Complete details of Series 15(a) tests are given in Tables 8 and 8(a) at end of thesis.

Series 2(a). /

Series 2(a).

Test Piece 1.- This was a spring of Series 2 (Wire No.10 S.W.G.), shortened from 5 effective coils to approximately 4 effective coils.

On testing this spring at a maximum stress of 41.24 tons/sq.in., with a range of stress of 24.74 tons/sq.in. and a mean stress of 28.87 tons/sq.in., complete failure occurred after 0.9 million reversals (14 hrs.), by cracking in one place - in the centre coil.

The oscilloscope showed that more or less oscillation of the coils occurred at all speeds beyond 1100 r.p.m., and up to 1250 r.p.m., the maximum observed. The oscillations had maximum amplitudes in the neighbourhood of the following speeds, viz., 1130, 1175, and 1230 r.p.m.

There was no oscillation of the coils at the speed of the test (1050 r.p.m.) - in fact, oscillation appeared to be entirely absent at all speeds within the limits 900-1100 r.p.m.

Modulus of Rigidity = 10.20×10^6 lb./sq.in.

In view of this test having resulted in fracture of the spring, a set of six (6) similar test pieces was now prepared.

Test Piece 3.- With this specimen there appeared to be more or less oscillation of the coils at all speeds. A test-speed of 1025 r.p.m. was chosen as being most satisfactory, the oscillations at this speed being very slight.

Complete failure occurred after 0.568 million reversals (9 hrs.) by cracking in two places - in the respective end coils.

At a maximum stress of 38.95 tons/sq.in., the range of stress was 20.51 tons/sq.in., and the mean stress 28.70 tons/sq.in.

This result would appear to be a case of premature failure due to "surging effect".

Modulus of Rigidity = 10.37×10^6 lb./sq. in.

Test /

<u>Test Piece 7</u>.- Complete failure occurred after 0.41 million reversals ($6\frac{1}{2}$ hrs.), being about 0.05 million reversals from first appearance of deformation. The spring failed by cracking in the <u>top</u> coil, with a second crack latterly developing in the centre coil.

At a maximum stress of 39.37 tons/sq.in., the range of stress was 20.87 tons/sq.in., and the mean stress 28.94 tons/sq.in.

Oscillation of the coils was very troublesome with this specimen also. Maximum amplitudes were observed at speeds of approximately 960 and 1180 r.p.m. At the test speed (1050 r.p.m.), the oscillations were almost indistinguishable.

Modulus of Rigidity = 10.48×10^6 lb./sq.in.

<u>Test Piece 4</u>.- The remaining specimens of Series 2(a) were all observed with the oscilloscope at their respective test loads, and found to be as subject to oscillation as were Test Pieces 3 and 7, so that it was useless to proceed further in an attempt to determine the Fatigue Range of these springs.

A final test was run with this test-piece (No.4), because of its particularly low value for the range of stress (19.18 tons/sq. in.); a value which normally should not result in fracture of the spring.

Complete failure occurred after 2.874 million reversals (41 hrs.), by cracking in one place - in the <u>bottom</u> coil, with a further crack developing in the centre coil.

The oscillations had maximum amplitudes at approximately 1040, 1080, 1135 and 1190 r.p.m., and were most marked at the latter speed (1190 r.p.m.). The test speed was fixed at 1065 r.p.m. as being most satisfactory for minimum oscillation.

Modulus of Rigidity = 10.53×10^6 lb./sq.in.

As /

As regards the specimens which were not fatigue tested, the oscillations had maximum values at the following approximate speeds:

Test Piece 2.- 930, 1045, 1090, 1145 and 1190 r.p.m.

Test Piece 5.- 900, 1040, 1085, 1140, 1200, and 1250 r.p.m.

Test Piece 6.- 1005, 1047, 1077, 1125, 1175, and 1227 r.p.m.

There was not much variation in the mean stresses for the Series, viz.:-

Mean Stress (Maximum = 28.94 tons/sq.in. (Test Piece 7)
(Minimum = 28.70 tons/sq.in. (Test Pieces 3 and 5).
(Average = 28.81 tons/sq.in.

The Modulus of Rigidity was fairly consistent over the Series, viz:-

Modulus of Rigidity (N) (Maximum = 10.67×10^6 lb./sq.in. (Test Piece 5
(Minimum = 10.04×10^6 lb./sq.in. (Test Piece 6
(Average = 10.35×10^6 lb./sq.in.

For complete details of these tests (Series 2(a)), see Tables 9 and 9(a) at end of thesis.

Series 5(a) - Test Piece 1.

This specimen was made from a spring of Series 5, shortened from 7 effective coils to approximately 4 effective coils. Differs from springs of Series 2(a) in respect of the coils having a smaller pitch, and being of smaller diameter. Same diameter of wire (No.10 S.W.G.).

Oscillation of the coils was found to be just as troublesome as with springs of Series 2(a), the oscillations being observed to have a maximum amplitude at approximately 1035 r.p.m. At speeds between the limits 1090-1230 r.p.m., the oscillations were so slight as to be almost indistinguishable, so the test speed was set at 1200 r.p.m.

However, complete failure occurred after only 0.633 million reversals ($8\frac{3}{4}$ hrs.), the spring breaking into four pieces, with a fourth crack developing in one coil midway between two of the breaks.

At a maximum stress of 39.46 tons/sq.in., the range of stress was 22.83 tons/sq.in., and the mean stress 28.04 tons/sq.in.

Modulus of Rigidity = 10.29×10^6 lb./sq.in.

Complete details of this test are included in Tables 9 and 9(a).

R E M A R K S.

Stoppages during any of the tabulated tests, required either for fitting the oscilloscope, or for measuring the "creep" of the spring, were for periods of a few minutes only. With these exceptions, all tabulated tests were perfectly continuous.

In this connection, it may be remarked that for the greatest facility in fitting the oscilloscope, the gearbox of this instrument was originally driven through an adapter incorporated as an extension of the spindle of the "Veeder" counter. Unfortunately, at this distance from the main cam-shaft, the oscilloscope gearbox vibrated so excessively as to be liable ultimately to damage not only itself but also the counter. Accordingly, it was arranged to drive the oscilloscope gearbox direct from the main camshaft, this being made possible by disconnecting the counter and its driving attachment, and providing a new adapter to take the place of the latter and drive the oscilloscope instead. Only an additional minute or two were required for this operation, the only drawback being that the use of the counter had to be dispensed with while the oscilloscope was attached. However, a close approximation to the total reversals during any such period was arrived at by noting the total running time and multiplying the average r.p.m. by this quantity. Such amounts were then added to the final counter reading, at the conclusion of the test concerned.

Involuntary stoppages were rather too frequent during the earlier fatigue tests, and in every case necessitated the abandonment of the current test, as they generally occurred during the night and were consequently of rather long duration.

The most frequent cause of breakdown was excessive wear of the roller in its bearings in the tappet, owing to failure of lubrication. Originally, the oil-pipe leading from the reservoir was branched, the upper branch discharging against the tappet at the top of the bush, and the lower branch discharging on to the roller and /

and cam. It was extremely difficult to ensure a steady flow of oil to these two points simultaneously; but, by making the flange of the bush in the form of a shallow cup, and using a single oil pipe discharging into it, the oil-drip could be so regulated as to keep this cup constantly full of oil, the flow through the bush to the roller and cam being found ample for their lubrication.

Trouble was also occasioned by wear of the tappet-rod where it passed through the upper spring collar into the top bush, mainly due to misalignment of the collar and bush; but also in a lesser degree to the softness of the rod material. This was obviated by spigoting the collar into the flange of the bush, and by employing rods of specially hard steel. When the top bush became worn, it was bored out and a liner inserted.

As mentioned in the description of the apparatus (p.8), the original leather belt drive from the motor to the machine gave so much trouble by failures at the joint, that recourse was made to the use of a composite rubber-and-canvas belt. Unfortunately, there was rapid deterioration of this material, owing to the impossibility of keeping the belt free from oil. Accordingly a leather belt, properly lace-jointed by the manufacturer, was fitted, and, after the slack due to initial stretching of the leather had been taken up by adjusting the position of the motor, no further trouble was experienced. Running was much quieter and there was very little slip in the drive.

Measurements of "creep" indicate that this takes place most rapidly in the early stages of the stressing, thereafter increasing very slowly, or ceasing altogether. However, immediately a crack begins to form in the wire, the spring naturally shortens rapidly as this crack develops, until complete fracture occurs.

Cracking of the springs in the present tests invariably commenced on the inside of the coil, the crack first of all developing along the axis of the wire, and thereafter extending obliquely to top and bottom of the section.

Actual "surging" (i.e., where the oscillations travel up and down the spring in the form of a wave) was not present in the case of any spring included in the fatigue tests, where oscillation of the coils was observed. (In this connection it may be noted that springs of Series 24 were observed to furnish definite cases of actual surging. These springs emitted clearly audible musical notes at certain speeds, the state of oscillation of the coils being plainly visible to the naked eye).

CONCLUSIONS.

The Mean Stress of the cycle does not appear to have any appreciable effect in lowering the value of the Fatigue Range.

Although the tests do not furnish sufficient evidence to justify any more definite statement in this connection, reference to the following abstracts of results from the three main Series of springs tested will show that the balance of evidence clearly inclines towards this conclusion.

Series No.	Average Mean Stress Tons/ sq.in.	Test Piece No.	Range of Stress. Tons/ sq.in.	Mean Stress. Tons/sq.in.	Reversals to Fracture. (Millions).
		4	25.98	26.71	0.453
		7	23.92	28.75	0.556
		5	23.09	28.24	0.530
12(a)	28.70	8	22.74	28.80	0.668
		13	21.82	30.61	2.0 to 2.5
		6	21.49	27.58	1.990
		6	21.74	22.42	0.446
		7	20.58	22.56	0.838
15(a)	22.50	1	19.87	22.54	8.196
		8	19.87	21.82	7.730
		3	22.28	27.43	1.000
		14	21.90	25.98	1.410
		4	21.58	25.47	1.516
4(a)	26.00	8	20.79	25.36	5.445
		9	20.58	25.73	6.066
		1	20.53	27.37	7.000
		11	20.21	26.87	11.81

The above results all plot evenly on the endurance curves for the respective series.

Considering Series 12(a) results, it will be seen that Test Piece 13 was tested at a mean stress of 30.61 tons/sq.in., as compared with 27.58 tons/sq.in. for Test Piece 6, so that if the mean stress had any appreciable effect in lowering the fatigue range, then the endurance of Test Piece 6 would reasonably be expected to be greater than that of Test Piece 13, particularly in view of the fact that Test Piece 6 endured the smaller range of stress. However, the very reverse is the case. (The exact number of reversals to fracture for Test Piece 13 was unknown, owing to the machine failing to stop when the spring broke; but it was certainly more than 2,000,000).

Further evidence may also be drawn from the tests of Test Pieces 4 and 7, whose endurances are in good proportion to the ranges of stress, although the mean stress for Test Piece 7 is appreciably greater than for Test Piece 4.

Turning now to Series 15(a) results, it may be noted that Test Pieces 1 and 8 were tested at the same value of the range of stress. Their respective endurances are in quite good agreement, and such divergence as there is, when considered in conjunction with the values of the mean stresses, further tends to support the statement regarding the effect of the mean stress upon the fatigue range.

Finally, in the case of Series 4(a) results, it may be observed that although there is some variation in the respective mean stresses - particularly in the cases of Test Pieces 1 and 3 - yet all the results plot very evenly on the endurance curve. There is certainly no evidence to show that the mean stress tends to lower the fatigue range.

To obtain really conclusive evidence, it would obviously be necessary to test two or three sets of similar springs at values of /

of the mean stress for each set which differed as widely as possible. Such differences in the values of the mean stress as exist in the above series of tests were quite unavoidable in most cases.

The following table gives the remaining results from the same three series of tests:-

Series No.	Average Mean Stress Tons/ sq.in.	Test Piece No.	Range of Stress. Tons/ sq.in.	Mean Stress Tons/ sq.in.	Reversals to Fracture (Millions). Theoretical Average. (From endurance Curve)	Reversals to Fracture (Millions). Actual (from test)
		2	26.53	28.99	0.30	0.73
	28.70	3	25.21	26.47	0.35	3.08
12(a)		9	21.98	29.08	1.50	3.10
		11	21.40	14.25	2.70	4.40
		10	21.10	19.50	3.80	1.08
		5	21.07	22.54	0.60	4.717
		11	20.90	22.49	0.70	7.960
15(a)	22.50	9	20.28	22.45	1.70	4.786
		3	20.16	22.45	2.10	11.710
		2	20.00	22.58	2.80	0.70
		2	23.75	25.75	0.560	1.300
		5	22.36	25.79	1.050	1.445
4(a)	26.00	7	22.29	24.88	1.100	8.848
		13	21.90	25.98	1.400	6.490
		10	21.86	24.21	1.460	5.540

It will be observed that, with the exception of Test Pieces 10 (Series 12(a)) and 2 (Series 15(a)), where the failures were premature, the endurances of all the above springs were much greater than would be expected from the respective ranges of stress endured.

These /

These results have already been discussed with reference to their bearing upon the question of the effect of the mean stress on the fatigue range, as follows - Series 12(a) (page 26); Series 15(a) (Page 31); and Series 4(a) (page 37).

Although they furnish no conclusive evidence in favour of the statement that the mean stress has no appreciable effect in lowering the value of the fatigue range, they certainly do not tend to disprove it in any way.

Premature failure of valve springs is, in the majority of cases, most certainly due to "surging" of the coils, causing a very appreciable increase in the normal stresses produced by cam action alone. That is to say, unequal strains are set up in addition to the uniform strain equal to that of the cam motion.

In the general case, this statement refers to springs which are operated, as in practice, at stresses which they should endure for an infinite number of repetitions without failure - i.e., the ranges of stress are "safe ranges" - but which in reality may fail owing to the increases of stress due to the presence of surging rendering the ranges of stress "unsafe ranges".

In the particular case of the present tests, where the springs were purposely tested to destruction at unsafe ranges, the serious effect of surging is evident from the obviously premature failures which occurred in cases where a certain amount of surging could not be avoided.

Abstracts of the results relevant to this question are given in the following table:-

Series No.	Average Mean Stress Tons/ sq.in.	Test Piece No.	Mean Stress. Tons/ sq.in.	Range of Stress. Tons/sq.in.	Reversals to Fracture. (Millions)
2	-	3	31.82	17.45	10.86
2(a)	28.81	1	28.87	24.74	0.900
		7	28.94	20.87	0.410
		3	28.70	20.51	0.568
		4	28.77	19.18	2.874
5(a)	-	1	28.04	22.83	0.633

Oscillation of the coils was greatest in the case of the specimen of Series 2, whereas in the case of Test Piece 1 of Series 2(a) there was no oscillation whatever. In the remaining cases oscillation was very slight.

The Fatigue Range for springs of the above diameter of wire (No.10 S.W.G.), could not be determined; but as this wire gave the highest value of the Fatigue Range from tests on the wires themselves before coiling, it seems reasonable to assume that it should also yield the highest value of the Fatigue Range in spring form.

As the Fatigue Ranges for the springs of the other diameters of wire are as follows:-

Wire No.8 S.W.G.:- $\pm$ 19.6 to $\pm$ 19.8 tons/sq.in. and
$\pm$ 20.5 to $\pm$ 20.9 tons/sq.in.

Wire No.11-12 S.W.G.:- $\pm$ 20.0 to $\pm$ 20.2 tons/sq.in.

it can safely be assumed to be at least $\pm$ 20.0 tons/sq.in. Relatively this is in quite good agreement with the endurance obtained with Test Piece 1 of Series 2(a), where there was no oscillation of the coils whatever.

Of the remaining tests of Series 2(a), the most striking result is that of Test Piece 4, which failed after only 2.874 million repetitions (41 hours running time) of a range of stress of 19.18 tons/sq.in. - obviously a range which should have been endured for an infinite number of repetitions without failure. Furthermore, the coil oscillation was extremely slight. This result is confirmed by the other two tests in this Series, and by the Series 5(a) test, in all of which premature failure also occurred, the oscillations being of much the same amplitudes.

As regards the Series 2 test, the oscillations were certainly more marked, although far from reaching the conditions of a case of true "surging". It is, therefore, perfectly obvious that, if the unequal strains set up by such slight oscillations of /

of the coils can so seriously affect the life of the spring, then in cases of actual "surging" the resultant stresses in the spring must be very large, the oscillations being much more pronounced, and their presence even visible to the naked eye.

The strength of the wire before coiling is no criterion of what its strength will be when it is used as a spring.

In the particular case of the present tests, it is evident that at least 50 per cent of the strength of the wire in simple form has been lost by using it coiled into springs. This is clearly shown by the following tabulation:-

Wire Diameter (S.W.G.)	Fatigue Range of Wire. (0.45 to 0.5 Ult. Torsional Strength) Tons/sq.in.	Fatigue Range of Springs Tons/sq.in.	
8	± 35.0 to ± 39.0	± 19.6	± 19.8
		± 20.5	± 20.9
10	± 40.0 to ± 44.0	not known	
11-12	± 39.0 to ± 43.0	± 20.0 to ± 20.2	

This result must be solely due to the coiling of the wire into springs, as in the present tests the question of the effect on the Fatigue Range of subsequent heat treatment does not enter into the matter at all, there having been no further treatment whatever of the wire after coiling.

Further referring to the above table, it will be seen that two values of the Fatigue Range are given for the springs of wire No.8 S.W.G. The reason for this is embodied under the following conclusion, which is merely a particular aspect of the statement already made.

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The radius of the helix to which any given diameter of wire is coiled would appear to have quite an appreciable effect on the value of the Fatigue Range for the resulting springs. That is to say, the smaller the radius of the helix into which the wire is coiled, the lower will be the value of the Fatigue Range for the springs, this effect being naturally more serious the greater the diameter of the wire itself.

Evidence apparently supporting this conclusion will be found on referring to the following table:-

Wire Diameter. (S.W.G.)	Ult. Torsional Strength (Tons/sq.in.)	Series No.	Average Mean Coil Diameter. (Ins.)	Fatigue Range of Springs. (Tons/sq.in.)
		6	0.970	Fractures at ± 14.0 and ± 14.05
8	78.1	15(a)	1.229	± 19.6 to ± 19.8
		12(a)	1.259	± 20.5 to ± 20.9
11-12	87.8	4(a)	1.033	± 20.0 to ± 20.2

This assumption that the coiling radius of the springs has quite an appreciable effect on the Fatigue Range appears to be the only explanation of the failure of springs of Series 6 at ranges of stress of the order of 14 tons/sq.in. It is further supported by the fact of springs of Series 12(a) giving an appreciably higher value of the Fatigue Range than springs of Series 15(a), the coiling radius of the former Series being the greater.

Where a relatively large diameter wire has been coiled to a particularly small radius, as in the case of springs of Series 6, the test results were in very poor agreement, viz:-

Series /

Series No.	Test Piece. No.	Range of Stress. (Tons/ sq.in.)	Reversals to Fracture. (Millions)	Mean Coil Diameter. (Inches)
	3	14.00	12.35	0.970
	4	14.05	10.83	0.972
	7	18.43	10.47	0.973
6	10	18.59	10.06	0.970
	6	18.66	5.33	0.974
	9	18.80	0.823	0.967
	8	19.31	5.308	0.966

According to the tests on Test Pieces 7 and 10, there should have been no failure of Test Pieces 3 and 4, and it will be observed that there is no practical difference in the coil diameters of these four springs to explain this discrepancy. This is also true of all the other series of springs tested. And, where there is an appreciable difference in the coil diameters, as in the cases of Test Pieces 8 and 9, the test results are very contradictory. Obviously a much more extensive series of tests would be necessary to justify the drawing of any definite conclusion. There can be no doubt, however, that the Fatigue Range for this series of springs is appreciably lower than for Series 15(a).

Considering now the case of Series 4(a), it will be seen that although the strength of this wire (11-12 S.W.G.) in simple form is 87.8 tons/sq.in., as compared with only 78.1 tons/sq.in. for wire No.8 S.W.G., yet a certain series of springs of the latter wire gave a higher value of the Fatigue Range. As the mean coil diameter of the springs of wire No.11-12 S.W.G. is 1.033 inches as compared with 1.259 inches for the springs of wire No.8 S.W.G., the assumption is that the stronger wire has been much more seriously weakened in process of coiling than the originally weaker wire.

In /

In any case it is obvious that the inner surfaces of springs must be the most highly strained, owing to the decreased radius of curvature, and, as it is at the inner surface that the shear stress has its maximum value, the conclusion to be drawn as to the effect of this on the life of the spring is just that which has already been indicated by the test results.

It has previously been noted that the initial cracking, which ultimately causes failure, invariably appears on the inner surface of the coil - all of which leads to this final conclusion that:-

To take the fullest advantage of the fundamental properties of the material of which they are composed, springs should be formed of wire of the smallest diameter, and the coil diameter should be the largest possible, in so far as is compatible with the work which they will be required to do and the working space which is available.

To conclude, it is apparent that the derivation of any fatigue formula of general application to helical springs is hardly feasible when the Fatigue Range may be so appreciably affected by a certain state of the material peculiar to the manufacture of any particular spring. This in addition to the difficulty of making a proper allowance for the serious increases of stress due to the possibly unknown presence of surging effect.

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TABLE 3 - STATIC COMPRESSION TESTS.

All Springs Hard Drawn Steel Wire (0.83% C.). No heat treatment after coiling.

Series No.	Dia. of Coils (Ins.)		δ Dia. of Wire.		Number of Effective Coils.	Free Length Inches.	Coil Dia. / Wire Dia.	Average Closing Load. lb.	Corresponding Max. Stress. (Tns/sq.in.)	Length when closed (Ins.)
	Overall.	Mean.	Fraction (Ins.)	S.W.G.						
+ 1		1.016	7/64	11-12	5	2.00	9.32	46	41.03	0.765
+ 2		1.000	1/8	10	5	2.10	8.00	76	44.24	0.885
+ 3		0.969	5/32	8	5	2.00	6.21	145	42.08	1.100
+ 4		1.016	7/64	11-12	7	2.60	9.32	42	37.45	1.000
+ 5	$1\frac{1}{8}$	1.000	1/8	10	7	2.65	8.00	72	41.91	1.135
+ 6		0.969	5/32	8	7	2.50	6.21	148	42.95	1.425
7		1.016	7/64	11-12	8	2.80	9.32	43	38.35	1.085
+ 8		1.000	1/8	10	8	2.85	8.00	71	41.33	1.260
+ 9		0.969	5/32	8	8	2.80	6.21	148	42.95	1.580
11		1.250	1/8	10	5	2.40	10.00	56	40.75	0.885
+12		1.219	5/32	8	5	2.40	7.81	115	41.98	1.100
14	$1\frac{3}{8}$	1.250	1/8	10	7	2.90	10.00	49	35.66	1.135
+15		1.219	5/32	8	7	2.80	7.81	97	35.41	1.430
17		1.250	1/8	10	8	3.20	10.00	48	34.92	1.295
18		1.219	5/32	8	8	3.10	7.81	95	34.67	1.570
20		1.500	1/8	10	5	2.60	12.00	43	37.55	0.887
21		1.469	5/32	8	5	2.50	9.42	78	34.33	1.100
23	$1\frac{5}{8}$	1.500	1/8	10	7	3.10	12.00	33	28.81	1.142
+24		1.469	5/32	8	7	3.10	9.42	74	32.56	1.420
26		1.500	1/8	10	8	3.45	12.00	35	30.56	1.265
+27		1.469	5/32	8	8	3.25	9.42	65	28.61	1.580
+2(a)	$1\frac{1}{8}$	1.000	1/8	10	4	1.66	8.00	79	45.98	0.740
+4(a)		1.016	7/64	11-12	$4\frac{1}{2}$	1.60	9.32	44	39.24	0.665
+12(a)	$1\frac{3}{8}$	1.219	5/32	8	$3\frac{1}{2}$	1.67	7.81	115	41.98	0.810
+15(a)		1.219	5/32	8	$4\frac{1}{2}$	1.74	7.81	100	36.51	0.930

Note:- Series Nos. marked + were fatigue tested.

T A B L E 4 - DETAILS OF SPRINGS.

Note:- O.E.N.L. = Outer Exhaust Valve Spring (450 Napier Lion). M.C. = Motor Car Valve Spring.

O.I.N.L. = " Inlet " " (" " "). H.D. = Hard Drawn Springs (0.83% C.)

Series No. . .	6	6	9	15	27	27	8	8	M.C.	N.L.	N.L.
Test Piece No. .	1	2	1	1	2	3	1	2	1	O.I.	O.E.
Outside Coil Dia. (Ins.) .	1.119	1.115	1.112	1.380	1.612	1.608	1.133	1.151	1.082	1.450	1.425
Mean Coil Dia. (Ins.) .	0.956	0.955	0.947	1.220	1.447	1.447	1.005	1.023	0.962	1.320	1.295
Wire Diameter (Ins.) .	0.163	0.160	0.165	0.160	0.165	0.161	0.128	0.128	0.120	0.130	0.130
S.W.G. . .	8	8	8	8	8	8	10	10	10-11	10	10
No. of Effective Coils . . .	7	7	8	7	8	8	8	8	10	7½	7½
Free Length of Spring (Ins.)	2.565	2.481	2.740	2.828	3.327	3.245	2.868	2.910	3.030	3.519	3.483
Length for Minimum Test Load (Ins.)	1.973	1.843	2.023	1.858	2.175	1.955	1.923	1.665	1.903	1.625	1.788
Effective Length for Minimum Test Load (Ins.)	1.690	1.515	1.710	1.500	1.860	1.680	1.600	1.443	1.780	1.390	1.450
Free Pitch of Coils (Ins.)	0.337	0.345	0.315	0.375	0.380	0.379	0.334	0.352	0.290	0.430	0.435
"Rate" of Spring (Lb./in.)	154	135	122	62	36	40	47.5	52	56	19	23
Closing Load (lb.)	150	150	150	93	63	69	72	71	70	47	54

Remarks Results of Fatigue Tests on these Springs given overleaf (Table 4(a)).

TABLE 4(a) - FATIGUE TESTS OF SPRINGS.

<u>Note</u>.- U = Unbroken Spring.

Series No. . .	6	6	9	15	27	27	8	8	M.C.	N.L.	N.L.
Test Piece No. .	1	2	1	1	2	3	1	2	1	O.I.	O.E.
Ultimate Torsional Strength of Wire (Tons/sq.in.)	78.1	78.1	78.1	78.1	78.1	78.1	89.3	89.3	-	-	-
Cam Lift (Ins.)	7/16	3/8	7/16	3/8	7/16	3/8	7/16	3/8	7/16	3/8	7/16
Cam-Shaft Speed (R.p.m.)	930	970	930	950	930	1050	900	950	1070	1025	958
Closing Load (lb.)	150	150	150	93	63	69	72	71	70	47	54
Maximum Test Load (lb.)	135	135	135	86	56.7	65	64.8	65	63	42.3	48.6
Minimum Test Load (lb.)	78.5	86.4	87.2	60	41.4	52.1	44.8	47.9	48.4	35.8	38.7
Maximum Stress (Tons/sq.in.)	39.21	39.21	39.20	31.42	24.97	28.63	37.70	37.80	39.87	28.90	32.60
Minimum Stress (Tons/sq.in.)	22.80	25.10	25.40	21.93	18.23	22.95	26.08	27.90	30.63	24.50	25.00
Range of Stress (Tons/sq.in.)	16.41	14.11	13.80	9.49	6.74	5.68	11.62	9.90	9.24	4.40	7.60
Mean Stress (Tons/sq.in.)	31.00	32.16	32.30	26.68	21.60	25.79	31.89	32.85	35.25	26.70	28.80
Reversals (Millions)	7.825	7.592	6.918	6.954	5.617	12.43	4.204	9.439	5.337	6.623	11.54
Duration of Test (Hrs.)	140	131	125	122	90	198	78	166	90	108	200
Final Closing Load (lb.)	148	143	136	90	61	63	70	60	69	46	53
"Creep" of Spring (Ins.)	0.061	0.074	0.090	0.124	0.031	0.103	0.058	0.185	0.013	0.019	0.008
Corresponding Reversals for "Creep" (Millions)	7.825	7.592	6.918	6.954	5.617	12.43	4.204	9.439	5.337	6.623	11.54
Stress equivalent of "Creep" (Tns/sq.in.)	2.36	2.76	2.63	2.64	0.410	1.63	1.50	5.33	0.461	0.247	0.123
Remarks	U.	U.	U.	U.	U.	U.	U.	U.	U.	U.	U.

TABLE 5 - DETAILS OF SPRINGS.

All Springs Hard Drawn Steel Wire (0.83% C.). No heat treatment after coiling.

Series No.	6	6	6	6	6	6	6	9	3	12	12	15
Test Piece No.	3	4	6	7	8	9	10	2	1	1	3	3
Outside Coil Dia. (Ins.)	1.130	1.132	1.134	1.132	1.126	1.127	1.130	1.120	1.150	1.419	1.419	1.387
Mean Coil Dia. (Ins.)	0.970	0.972	0.974	0.973	0.966	0.967	0.970	0.960	0.990	1.259	1.260	1.227
Wire Dia. (Ins.)	0.160	0.160	0.160	0.159	0.160	0.160	0.160	0.160	0.160	0.160	0.159	0.160
S.W.G.	8	8	8	8	8	8	8	8	8	8	8	8
No. of Effective Coils	7	7	7	7	7	7	7	8	5	5	5	7
Free Length of Spring (Ins.)	2.538	2.530	2.546	2.475	2.525	2.523	2.532	2.758	1.950	2.450	2.360	2.772
Length for Minimum Test Load (Ins.)	1.820	1.814	1.927	1.927	1.940	1.915	1.938	1.965	1.473	1.485	1.618	1.825
Effective Length for Minimum Test Load (Ins.)	1.556	1.550	1.648	1.650	1.660	1.637	1.650	1.676	1.330	1.270	1.385	1.560
Free Pitch of Coils (Ins.)	0.330	0.325	0.330	0.325	0.330	0.330	0.330	0.325	0.345	0.450	0.445	0.370
Pitch of Coils for Min. Test Load (Ins.)	0.237	0.233	0.245	0.253	0.255	0.250	0.252	0.232	0.260	0.275	0.305	0.243
"Rate" of Spring (Lb./In.)	135	130	130	135	137	140	132	125	175	87	87	75
Closing Load (Lb.)	150	148	150	143	154	149	150	150	150	121	114	95
Modulus of Rigidity (N) x 10^6 (Lb./sq.in.)	10.05	9.85	9.94	10.24	10.08	10.14	9.65	9.80	10.57	9.96	10.02	11.0

Remarks: Results of Fatigue Tests on these Springs given overleaf (Table 5(a)).

TABLE 5(a) - FATIGUE TESTS OF SPRINGS.

Note.- B = Broken Spring. U = Unbroken Spring.

Series No.	6	6	6	6	6	6	6	9	3	12	12	15
Test Piece No.	3	4	6	7	8	9	10	2	1	1	3	3
Ultimate Torsional Strength of Wire (Tns/sq.in.)	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1
Cam Lift (Ins.)	3/8	3/8	1/2	1/2	1/2	1/2	1/2	3/8	3/8	3/8	1/2	3/8
Cam-Shaft Speed (R.p.m.)	1000	1100	1000	1000	1100	1300	1300	1100	1100	1100	1000	1300
Closing Load (Lb.)	150	148	150	143	154	149	150	150	150	121	114	95
Max. Test Load(Lb.)	145	146	149	142	152	148	148	147	147	119	113	93
Min.Test Load (Lb.)	93	94	80	75	80	78	79	98	75	80	61	63
Maximum Stress (Tns/sq.in.)	39.04	39.41	40.29	39.07	40.76	39.73	39.86	39.17	40.40	41.59	40.27	31.67
Minimum Stress (Tns/sq.in.)	25.04	25.36	21.63	20.64	21.45	20.93	21.27	26.11	20.60	27.96	21.74	21.45
Range of Stress (Tns/sq.in.)	14.0	14.05	18.66	18.43	19.31	18.80	18.59	13.06	19.80	13.63	18.53	10.22
Mean Stress (Tns/sq.in.)	32.04	32.39	30.96	29.86	31.10	30.33	30.57	32.64	30.50	34.78	31.0	26.56
Reversals (Millions)	12.35	10.83	5.33	10.47	5.308	0.823	10.06	17.20	2.598	14.12	12.00	12.16
Duration of Test (Hrs.)	210	164	88	174	80½	10½	136	263	39½	230	200	156
Final Closing Load (Lb.)	-	-	-	-	-	-	-	140	-	110	105	85
"Creep" of Spring (Ins.)	-	-	-	-	-	-	-	0.108	-	0.082	0.060	0.062
Corresponding Reversals for "Creep" (Millions)	-	-	-	-	-	-	-	17.20	-	14.12	12.00	12.16
Stress equivalent of "Creep" (Tns/sq.in.)	-	-	-	-	-	-	-	3.60	-	2.49	1.86	1.58
Remarks	B.	B.	B.	B.	B.	B.	B.	U.	B.	U.	U.	U.

T A B L E 6 - DETAILS OF SPRINGS.

All Springs Hard Drawn Steel Wire (0.83% C.). No heat treatment after coiling.

Series No.	12(a)												
Test Piece No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Outside Coil Dia. (Ins.)	1.438	1.410	1.415	1.435	1.415	1.425	1.422	1.405	1.413	1.420	1.419	1.412	1.403
Mean Coil Dia. (Ins.)	1.279	1.251	1.256	1.276	1.256	1.266	1.263	1.246	1.254	1.261	1.260	1.253	1.244
Wire Dia. (Ins.)	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159	0.159
S.W.G.	8	8	8	8	8	8	8	8	8	8	8	8	8
No. of Effective Coils	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$	$3\frac{1}{2}$
Free Length of Spring (Ins.)	1.768	1.700	1.690	1.645	1.648	1.665	1.665	1.665	1.620	1.650	1.638	1.650	1.640
Length for Min. Test Load (Ins.)	1.234	1.333	1.342	1.330	1.251	1.263	1.244	1.261	1.181	1.450	1.545	1.122	1.181
Effective Length for Min. Test Load (Ins.)	1.055	1.140	1.150	1.137	1.070	1.080	1.062	1.077	1.010	1.240	1.322	0.960	1.010
Free Pitch of Coils (Ins.)	0.445	0.450	0.450	0.440	0.445	0.450	0.450	0.450	0.440	0.450	0.445	0.445	0.445
Pitch of Coils for Min. Test Load (Ins.)	0.310	0.353	0.357	0.355	0.340	0.340	0.335	0.340	0.320	0.395	0.420	0.303	0.320
"Rate" of Spring (Lb./in.)	120	133	128	134	132	127	130	134	135	135	130	129	137
Closing Load (lb.)	111	120	112	112	114	110	116	116	115	120	116	115	120
Modulus of Rigidity (N) x 10^6 (lb./sq.in.)	11.0	10.75	10.47	11.5	10.47	10.32	10.5	10.38	10.58	10.84	10.42	10.16	10.56
Remarks	Results of Fatigue Tests on these Springs given overleaf - Table 6(a).												

TABLE 6(a) - FATIGUE TESS OF SPRINGS.

Note.- B = Broken Spring. U = Unbroken Spring.

Series No.	12(a)												
Test Piece No.	1	2	3	4	5	6	7	8	9	10	11	12	13
Ultimate Torsional Strength of Wire (Tns./sq.in.)	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1
Cam Lift (Ins.)	3/8	1/2	1/2	1/2	7/16	7/16	7/16	7/16	3/8	1/2	1/2	5/16	3/8
Cam-Shaft Speed (R.p.m.)	1100	1100	1100	1100	1100	1100	1300	900	1100	1100	1200	1300	1300
Closing Load (lb.)	111	120	112	112	114	110	116	116	115	120	116	115	120
Max. Test Load (lb.)	109	118	110	110	112	107	114	114	113	84	70	113	118
Min. Test Load (lb.)	58	43	39	38	47	47	47	49	51	25	10	57	56
Max. Stress (Tons/sq.in.)	39.43	41.75	39.07	39.70	39.78	38.32	40.71	40.17	40.07	30.00	24.95	40.04	41.52
Minimum Stress (Tns/sq.in.)	20.98	15.22	13.86	13.72	16.69	16.83	16.79	17.43	18.09	8.90	3.55	20.19	19.70
Range of Stress (Tns/sq.in.)	18.45	26.53	25.21	25.98	23.09	21.49	23.92	22.74	21.98	21.10	21.40	19.85	21.82
Mean Stress (Tns/sq.in.)	30.21	28.99	26.47	26.71	28.24	27.58	28.75	28.80	29.08	19.5	14.25	30.12	30.61
Reversals (Millions)	11.89	0.730	3.08	0.453	0.530	1.99	0.556	0.668	3.10	1.08	4.40	11.30	2.0 to 2.5
Duration of Test (Hrs.)	180	11	47	7	8	30	7	12½	47	16½	61	145	26-32
Final Closing Load (Lb.)	108	-	-	-	-	-	-	-	-	-	-	110	-
"Creep" of Spring (Ins.)	0.020	-	-	-	-	-	-	-	-	-	-	0.030	-
Corresponding Reversals for "Creep" (Millions)	11.89	-	-	-	-	-	-	-	-	-	-	11.30	-
Stress Equivalent of "Creep" (Tns/sq.in.)	0.87	-	-	-	-	-	-	-	-	-	-	1.37	-
Remarks	U.	B.	B.	B.	B.	B.	B.	B.	B.	B.	B.	U.	B.

TABLE 7 - DETAILS OF SPRINGS.

All Springs Hard Drawn Steel Wire (0.83% C.). - No heat treatment after coiling.

Series No.	4(a)												
Test Piece No.	1	2	3	4	5	7	8	9	10	11	12	13	14
Outside Coil Dia. (Ins.)	1.140	1.155	1.142	1.150	1.145	1.143	1.140	1.143	1.142	1.145	1.145	1.144	1.144
Mean Coil Dia. (Ins.)	1.029	1.044	1.031	1.039	1.034	1.032	1.029	1.032	1.031	1.034	1.034	1.033	1.033
Wire Dia. (Ins.)	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111	0.111
S. W. G.	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12	11-12
No. of Effective Coils	4½	4½	4½	4½	4½	4½	4½	4½	4½	4½	4½	4½	4½
Free Length of Spring (Ins.)	1.620	1.545	1.640	1.600	1.600	1.588	1.500	1.623	1.605	1.615	1.600	1.625	1.625
Length for Min. Test Load (Ins.)	1.169	1.164	1.170	1.157	1.185	1.182	1.082	1.164	1.189	1.140	1.113	1.189	1.189
Effective Length for Min. Test Load (Ins.)	1.000	0.995	1.000	0.990	1.012	1.010	0.925	0.995	1.070	0.975	0.955	1.070	1.070
Free Pitch of Coils (Ins.)	0.355	0.350	0.360	0.350	0.350	0.350	0.350	0.360	0.355	0.350	0.355	0.355	0.355
Pitch of Coils for Min. Test Load (Ins.)	0.257	0.265	0.257	0.253	0.260	0.260	0.253	0.258	0.263	0.247	0.247	0.260	0.260
"Rate" of Spring (Lb./in.)	47	48	45	44	46	46	48	43	44	45	43	44	45
Closing Load (Lb.)	47	44	46	43	44	44	43	43	42	45	45	45	45
Modulus of Rigidity (N) x 10^6 (lb./sq.in.)	10.78	10.94	10.40	10.40	10.46	10.39	10.19	9.71	10.42	10.48	9.77	10.73	10.97
Remarks	Results of Fatigue Tests on these Springs given overleaf - Table 7(a)												

TABLE 7(a) - FATIGUE TESTS OF SPRINGS.

Note.- B = Broken Spring. U = Unbroken Spring.

Series No.	4(a)												
Test Piece No.	1	2	3	4	5	7	8	9	10	11	12	13	14
Ultimate Torsional Strength of Wire (Tns/sq.in.)	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8	87.8
Cam Lift (Ins.)	1/2	1/2	1/2	1/2	1/2	1/2	7/16	1/2	1/2	7/16	7/16	1/2	1/2
Cam-Shaft Speed (R.p.m.)	1100	1100	1100	1100	1100	1100	1000	1100	1000	1000	1000	1000	1000
Closing Load (lb.)	47	44	46	43	44	44	43	43	42	45	45	45	45
Max. Test Load (lb.)	44	43	45	42	43	42	42	42	41	43	43¼	43	43
Min. Test Load (lb.)	20	16	19	17	17	16	17½	18	15½	19½	20	17½	17½
Max. Stress (Tns/sq.in.)	37.63	37.63	38.57	36.26	36.97	36.02	35.75	36.02	35.14	36.97	37.18	36.93	36.93
Min. Stress (Tns/sq.in.)	17.10	13.88	16.29	14.68	14.61	13.73	14.96	15.44	13.28	16.76	17.18	15.03	15.03
Range of Stress (Tns/sq.in.)	20.53	23.75	22.28	21.58	22.36	22.29	20.79	20.58	21.86	20.21	20.00	21.90	21.90
Mean Stress (Tns/sq.in.)	27.37	25.75	27.43	25.47	25.79	24.88	25.36	25.73	24.21	26.87	27.18	25.98	25.98
Reversals (Millions)	7.00	1.30	1.00	1.516	1.445	8.848	5.445	6.066	5.54	11.81	12.24	6.49	1.41
Duration of Test (Hrs.)	106	19¾	15	23	22	134	90¾	92	92½	197	204	108	22½
Final Closing Load (lb.)	-	-	-	-	-	-	-	-	-	-	40	-	-
"Creep" of Spring (Ins.)	-	-	-	-	-	-	0.010	-	-	0.015	0.015	0.025	-
Corresponding Reversals for "Creep"(Millions)	-	-	-	-	-	-	4.50	-	-	10.00	5.24	5.00	-
Stress Equivalent of "Creep" (Tns/sq.in.)	-	-	-	-	-	-	0.41	-	-	0.58	0.55	0.87	-
Remarks	B.	B.	B.	B.	B.	B.	B.	B.	B.	B.	U.	B.	B.

TABLE 8 - DETAILS OF SPRINGS.

All Springs Hard Drawn Steel Wire (0.83% C.). No heat treatment after coiling.

Series No.	15(a)										
Test Piece No.	1	2	3	4	5	6	7	8	9	10	11
Outside Coil Dia. (Ins.)	1.386	1.387	1.385	1.390	1.390	1.392	1.386	1.387	1.390	1.375	1.387
Mean Coil Dia. (Ins.)	1.227	1.229	1.227	1.231	1.231	1.234	1.229	1.230	1.233	1.218	1.229
Wire Diameter (Ins.)	0.159	0.158	0.158	0.159	0.159	0.158	0.157	0.157	0.157	0.157	0.158
S.W.G.	8	8	8	8	8	8	8	8	8	8	8
No. of Effective Coils	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$	$4\frac{1}{2}$
Free Length of Spring (Ins.)	1.685	1.695	1.720	1.715	1.750	1.740	1.730	1.770	1.820	1.772	1.787
Length for Minimum Test Load (Ins.)	1.375	1.402	1.424	1.387	1.435	1.445	1.437	1.437	1.500	1.417	1.500
Effective Length for Min. Test Load (Ins.)	1.180	1.200	1.220	1.190	1.230	1.235	1.227	1.230	1.280	1.215	1.283
Free Pitch of Coils (Ins.)	0.365	0.380	0.375	0.370	0.375	0.370	0.375	0.375	0.380	0.375	0.375
Pitch of Coils for Min. Test Load (Ins.)	0.295	0.315	0.310	0.290	0.295	0.305	0.312	0.305	0.310	0.300	0.310
"Rate" of Spring (Lb./In.)	116	125	124	121	115	115	124	117	110	117	117
Closing Load (Lb.)	92	102	100	100	98	99	104	100	102	102	104
Modulus of Rigidity (N) x 10^6 (lb./sq.in.)	10.73	11.61	11.76	11.86	11.27	11.37	12.12	11.76	11.40	11.41	11.90
Remarks	Results of Fatigue Tests on these Springs given overleaf - Table 8(a).										

TABLE 8(a) - **FATIGUE TESTS OF SPRINGS.**

Note.- B = Broken Spring. U = Unbroken Spring.

Series No.	15(a)										
Test Piece No.	1	2	3	4	5	6	7	8	9	10	11
Ultimate Torsional Strength of Wire (Tons/sq.in.)	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1	78.1
Cam Lift (Ins.)	7/16	7/16	7/16	7/16	1/2	1/2	7/16	7/16	1/2	7/16	1/2
Cam-Shaft Speed (R.p.m.)	1100	1200	1200	1100	1075	1075	1075	1150	1100	1075	1250
Closing Load (lb.)	92	102	100	100	98	99	104	100	102	102	104
Max. Test Load (Lb.)	91½	92	92	92½	95	94	91	90	90	92	93
Min. Test Load (Lb.)	34	35½	35	36¼	34½	32½	34	35	34	38	34
Maximum Stress (Tns/sq.in.)	31.75	32.58	32.53	32.20	33.07	33.29	32.85	32.52	32.59	32.92	32.94
Minimum Stress (Tns/sq.in.)	11.88	12.58	12.37	12.62	12.00	11.55	12.27	12.65	12.31	13.59	12.04
Range of Stress (Tns/sq.in.)	19.87	20.00	20.16	19.58	21.07	21.74	20.58	19.87	20.28	19.33	20.90
Mean Stress (Tns/sq.in.)	21.82	22.58	22.45	22.41	22.54	22.42	22.56	22.54	22.45	23.25	22.49
Reversals (Millions)	7.73	0.70	11.71	12.50	4.717	0.446	0.838	8.196	4.786	12.50	7.960
Duration of Test (Hrs)	117	9¾	166	189½	73	7	13	119	72½	194	106
Final Closing Load (Lb.)	-	-	-	94	-	-	-	-	-	98	-
"Creep" of Spring (Ins.)	0.020	-	0.020	0.035	0.010	-	-	0.010	0.020	0.022	0.014
Corresponding Reversals for "Creep" (Millions)	6.00	-	9.50	12.50	2.75	-	-	5.00	3.00	12.50	5.750
Stress Equivalent of "Creep" (Tns/sq.in.)	0.805	-	0.877	1.48	0.400	-	-	0.423	0.797	0.921	0.580
Remarks	B.	B.	B.	U.	B.	B.	B.	B.	B.	U.	B.

TABLE 9 - DETAILS OF SPRINGS.

All Springs Hard Drawn Steel Wire (0.83% C.). No heat treatment after coiling.

Series No.	1	1	2	2	2	2(a)	2(a)	2(a)	2(a)	2(a)	2(a)	2(a)	5(a)
Test Piece No.	1	2	1	2	3	1	2	3	4	5	6	7	1
Outside Coil Dia. (Ins.)	1.187	1.188	1.162	1.168	1.167	1.163	1.165	1.173	1.165	1.162	1.153	1.160	1.143
Mean Coil Dia. (Ins.)	1.076	1.077	1.034	1.040	1.039	1.037	1.038	1.047	1.039	1.036	1.026	1.034	1.016
Wire Dia. (Ins.)	0.111	0.111	0.128	0.128	0.128	0.126	0.126	0.127	0.126	0.126	0.127	0.126	0.127
S.W.G.	11-12	11-12	10	10	10	10	10	10	10	10	10	10	10
No. of Effective Coils	5	5	5	5	5	4	4	4	4	4	4	4	4
Free Length of Spring (Ins.)	2.020	2.012	2.075	2.100	2.095	1.643	1.655	1.675	1.695	1.625	1.630	1.617	1.552
Length for Min. Test Load (Ins.)	1.172	1.237	1.284	1.274	1.360	1.235	1.244	1.258	1.300	1.242	1.245	1.215	1.187
Effective Length for Min. Test Load (Ins.)	1.020	1.060	1.093	1.080	1.170	1.060	1.062	1.075	1.113	1.065	1.065	1.040	1.020
Free Pitch of Coils (Ins.)	0.410	0.400	0.390	0.390	0.390	0.385	0.390	0.397	0.395	0.380	0.390	0.385	0.350
Pitch of Coils for Min. Test Load (Ins.)	0.238	0.266	0.240	0.237	0.253	0.287	0.293	0.297	0.302	0.290	0.298	0.290	0.270
"Rate" of Spring (Lb./in.)	40	40	67	65	65	76	80	77	80	81	84	83	84
Closing Load (lb.)	48	49	78	80	78	78	80	77	80	78	80	80	72
Modulus of Rigidity (N) x 10^6 (lb./sq.in.	11.30	10.63	10.16	9.99	10.24	10.21	10.17	10.37	10.53	10.67	10.04	10.48	10.29

Remarks Results of Fatigue Tests on these Springs given overleaf - Table 9(a).

TABLE 9(a) - FATIGUE TESTS OF SPRINGS.

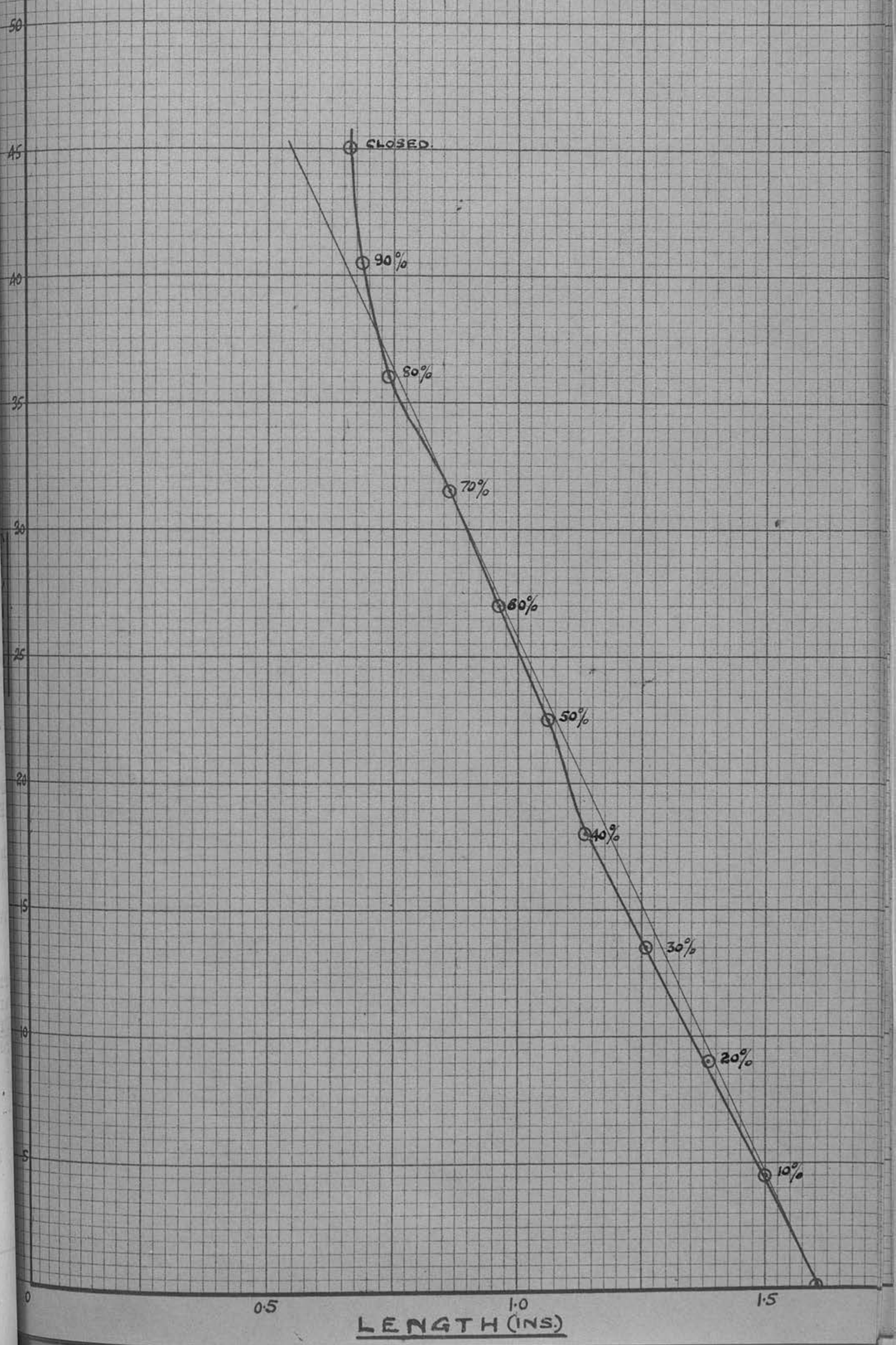
Note.- B = Broken Spring. U = Unbroken Spring.

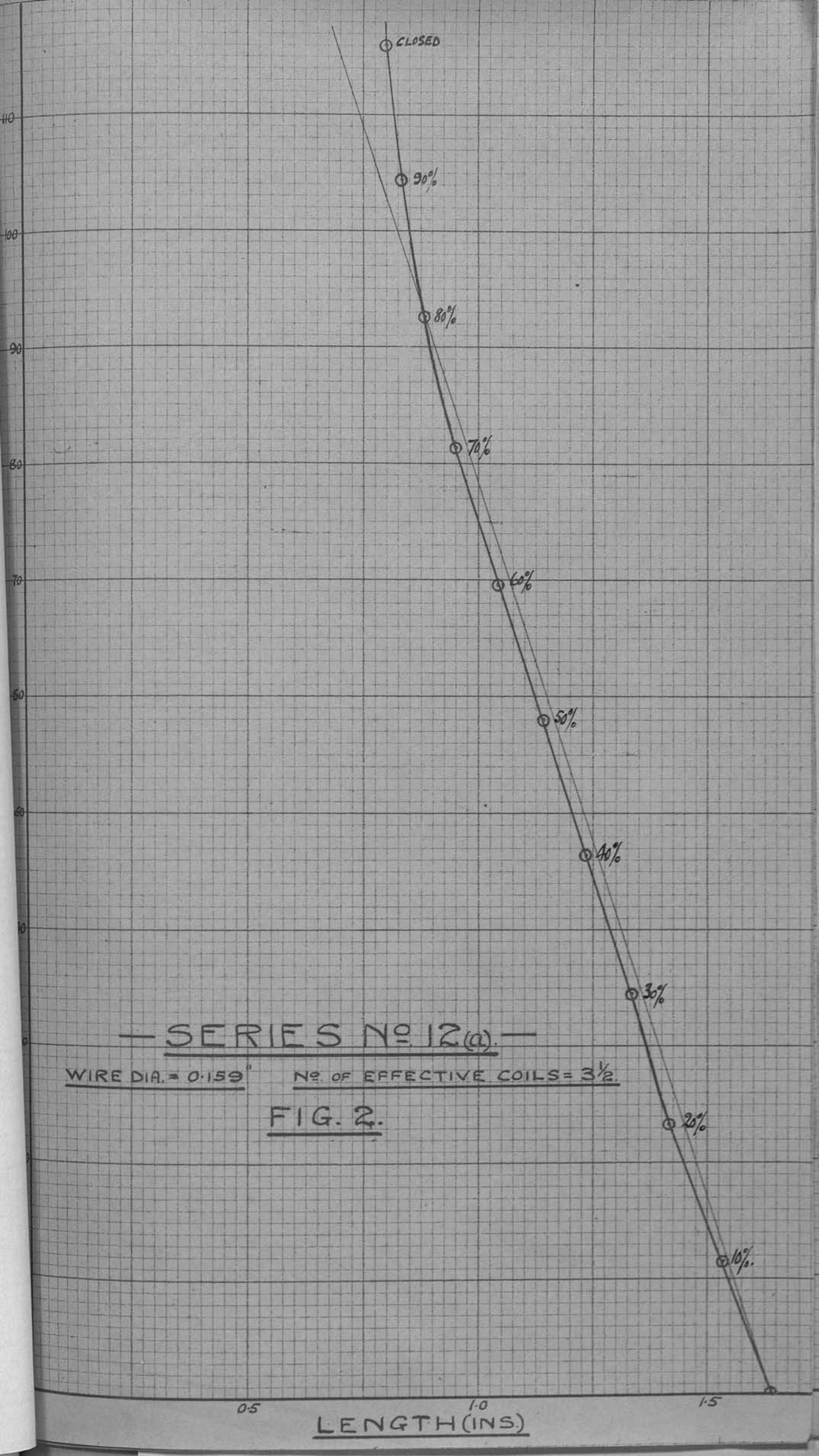
Series No.	1	1	2	2	2	2(a)	2(a)	2(a)	2(a)	2(a)	2(a)	2(a)	5(a)
Test Piece No.	1	2	1	2	3	1	2	3	4	5	6	7	1
Ultimate Torsional Strength of Wire (Tns/sq.in.)	87.8	87.8	89.3	89.3	89.3	89.3	89.3	89.3	89.3	89.3	89.3	89.3	89.3
Cam Lift (Ins.)	3/8	7/16	3/8	3/8	7/16	1/2	7/16	7/16	7/16	7/16	7/16	7/16	7/16
Cam-Shaft Speed (R.p.m.)	1100	1100	1100	1300	1100	1050	-	1025	1165	-	-	1050	1200
Closing Load (lb.)	48	49	78	80	78	78	80	77	80	78	80	80	72
Max. Test Load(lb.)	46	48	77	79	72	70	68	$65\frac{1}{2}$	65	$67\frac{1}{2}$	70	67	70
Min. Test Load(lb.)	$31\frac{1}{2}$	30	51	50	41	28	32	31	$32\frac{1}{2}$	30	$31\frac{1}{2}$	$31\frac{1}{2}$	$29\frac{1}{2}$
Max. Stress (Tns/sq.in.)	41.16	42.98	43.16	44.53	40.54	41.24	39.16	38.95	38.36	39.74	39.86	39.37	39.46
Min. Stress (Tns/sq.in.)	28.16	26.86	28.59	28.19	23.09	16.50	18.43	18.44	19.18	17.66	17.94	18.50	16.63
Range of Stress (Tns/sq.in.)	13.00	16.12	14.57	16.34	17.45	24.74	20.73	20.51	19.18	22.08	21.92	20.87	22.83
Mean Stress (Tns/sq.in.)	34.66	34.92	35.88	36.36	31.82	28.87	28.80	28.70	28.77	28.70	28.90	28.94	28.04
Reversals (Millions)	15.40	14.78	12.23	12.81	10.86	0.900	-	0.568	2.874	-	-	0.410	0.633
Duration of Test (Hrs)	234	224	186	164	167	14	-	9	41	-	-	$6\frac{1}{2}$	$8\frac{3}{4}$
Final Closing Load (lb.)	41	41	72	80	-	-	-	-	-	-	-	-	-
"Creep" of Spring (Ins.)	0.025	0.032	0.067	0.300	-	-	-	-	0.040	-	-	-	-
Corresponding Reversals for "Creep" (Millions)	15.40	14.78	12.23	12.81	-	-	-	-	2.00	-	-	-	-
Stress Equivalent of "Creep" (Tns/sq.in.	0.895	1.15	2.52	-	-	-	-	-	1.89	-	-	-	-
Remarks	U.	U.	U.	U. (Heat 135° C.)	B. (Surge)	B.	-	B.	B.	-	-	B.	B.

— SERIES No. 4(a). —

WIRE DIA = 0·111". No. OF EFFECTIVE COILS = 4½.

FIG. 1





— SERIES No. 12(a). —

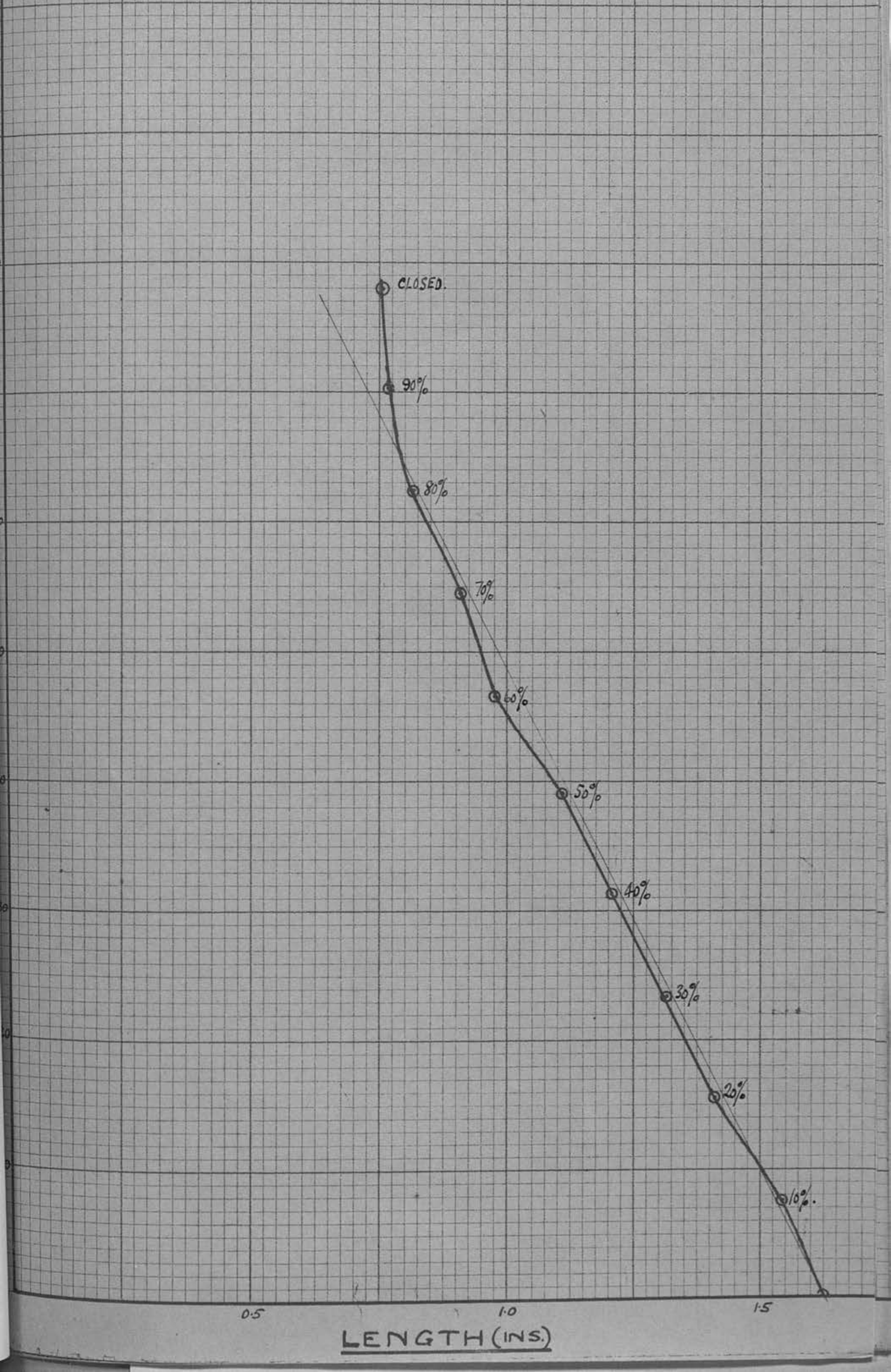
WIRE DIA. = 0.159" No. OF EFFECTIVE COILS = 3½.

FIG. 2.

— SERIES No. 2(a). —

WIRE DIA. = 0·126. No. OF EFFECTIVE COILS = 4.

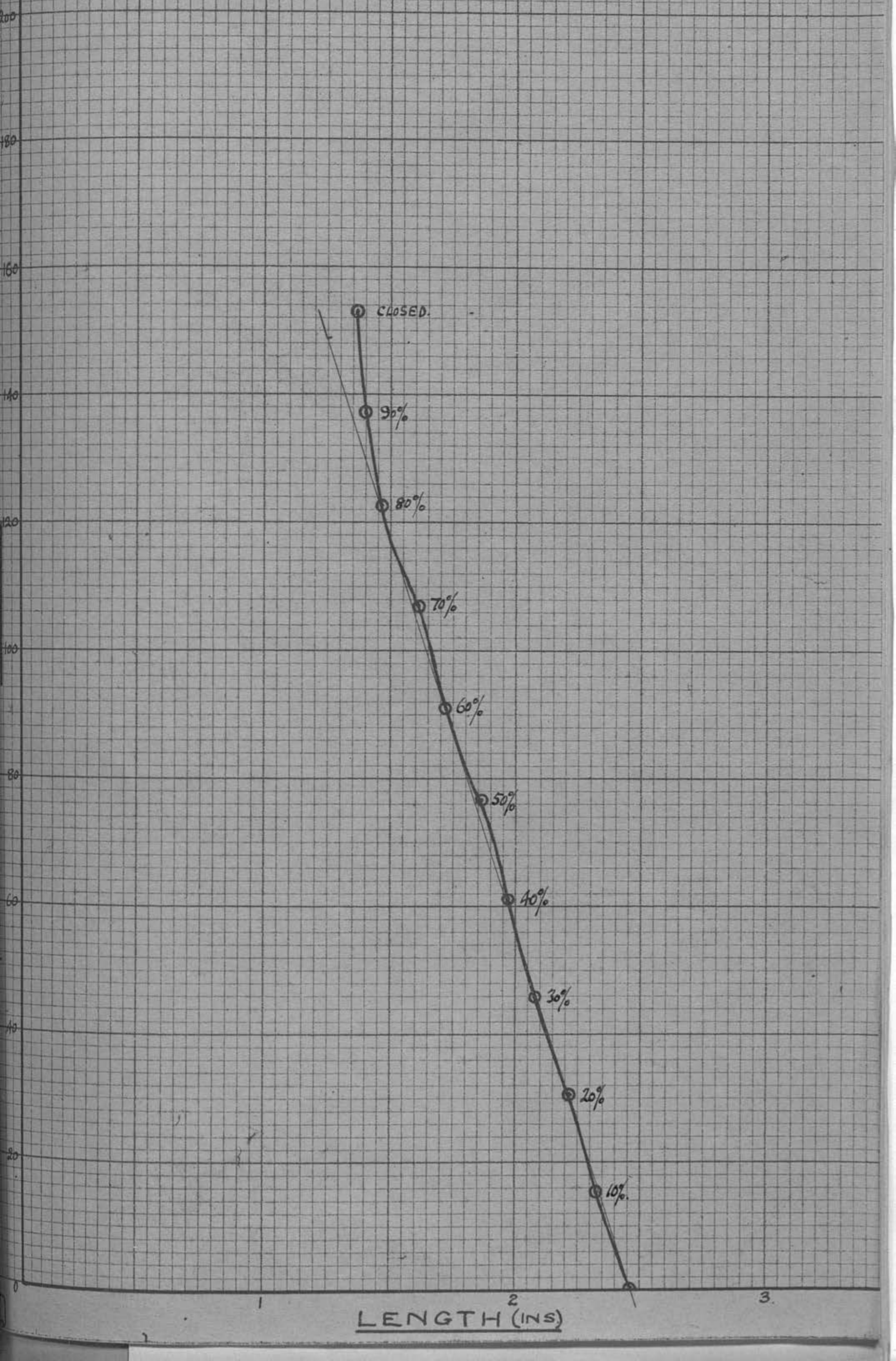
FIG. 3.



— SERIES No. 6. —

WIRE DIA. = 0·160" No. OF EFFECTIVE COILS = 7.

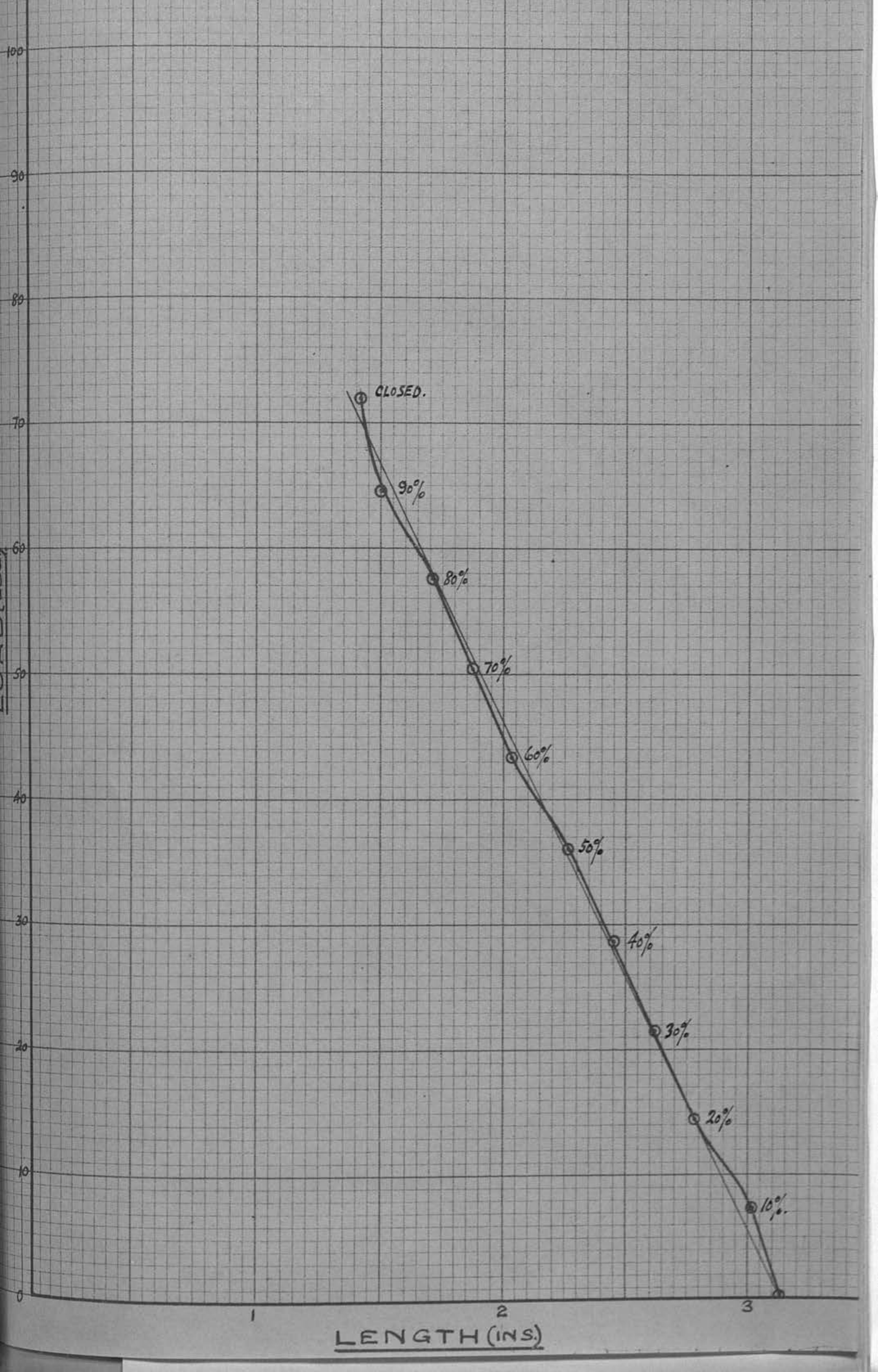
FIG. 4.



— SERIES No. 24. —

WIRE DIA. = 0·159" No. OF EFFECTIVE COILS = 7.

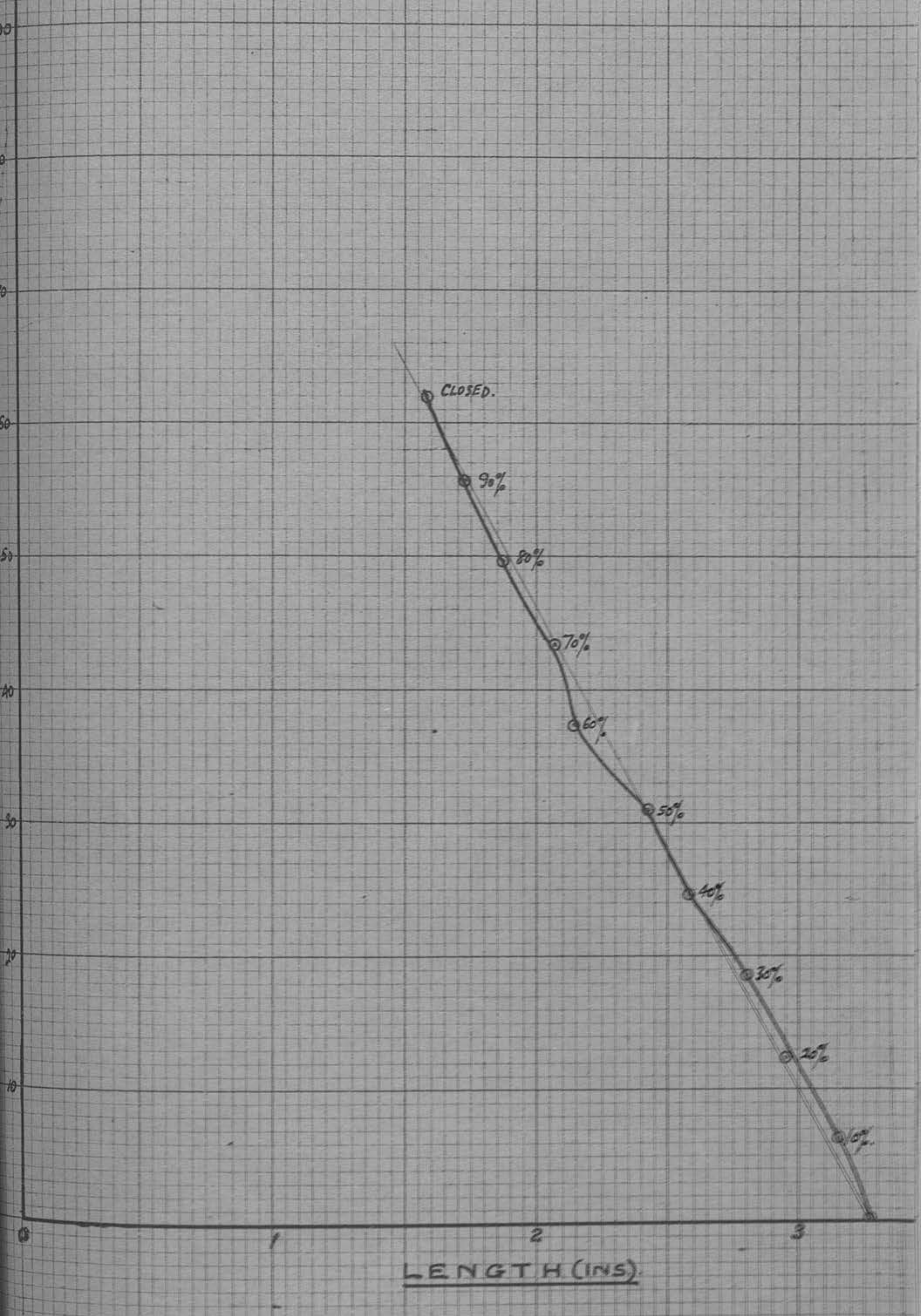
FIG. 5.



—SERIES Nº. 27.—

WIRE DIA. = 0·160". Nº. OF EFFECTIVE COILS = 8.

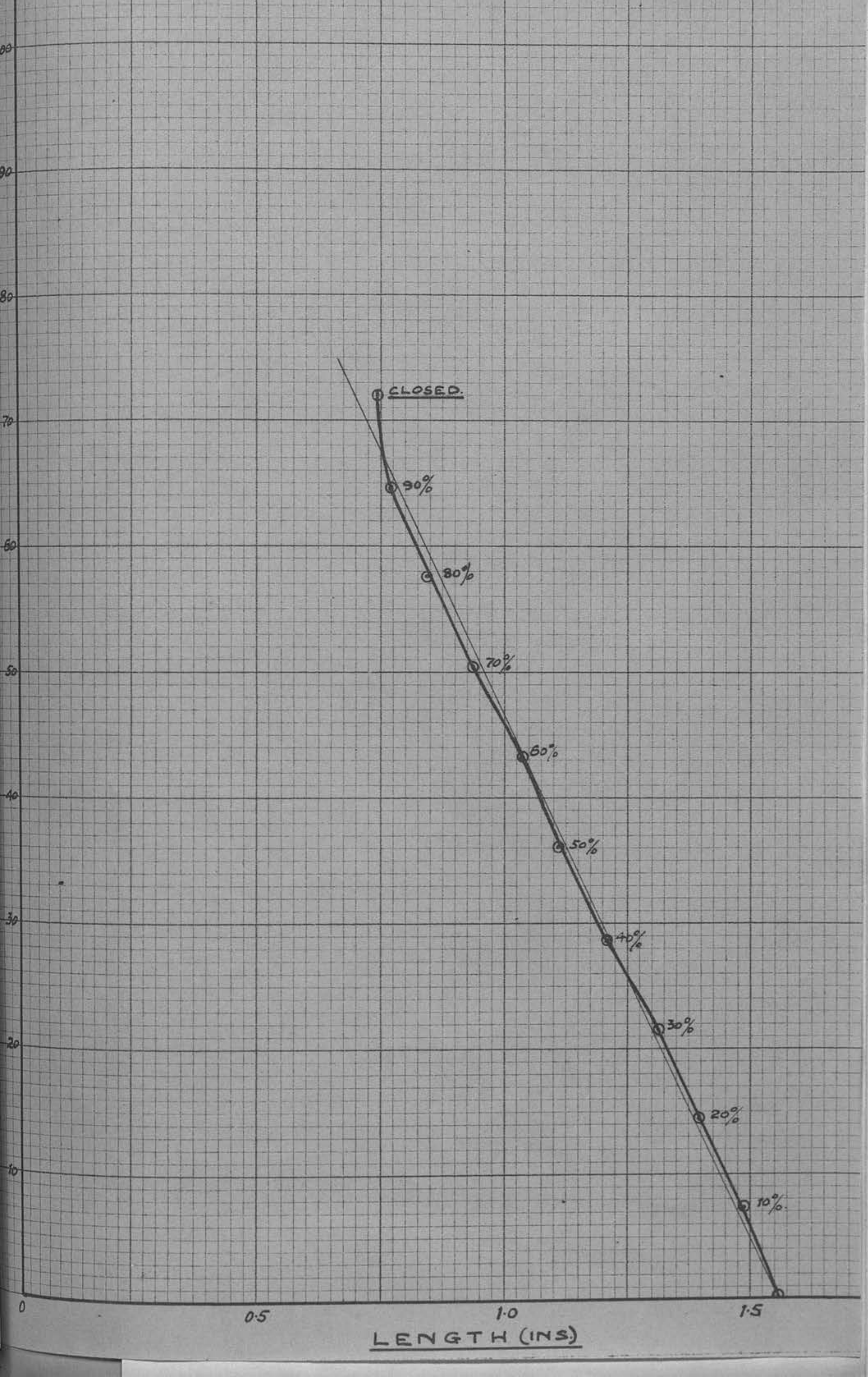
FIG. 6.

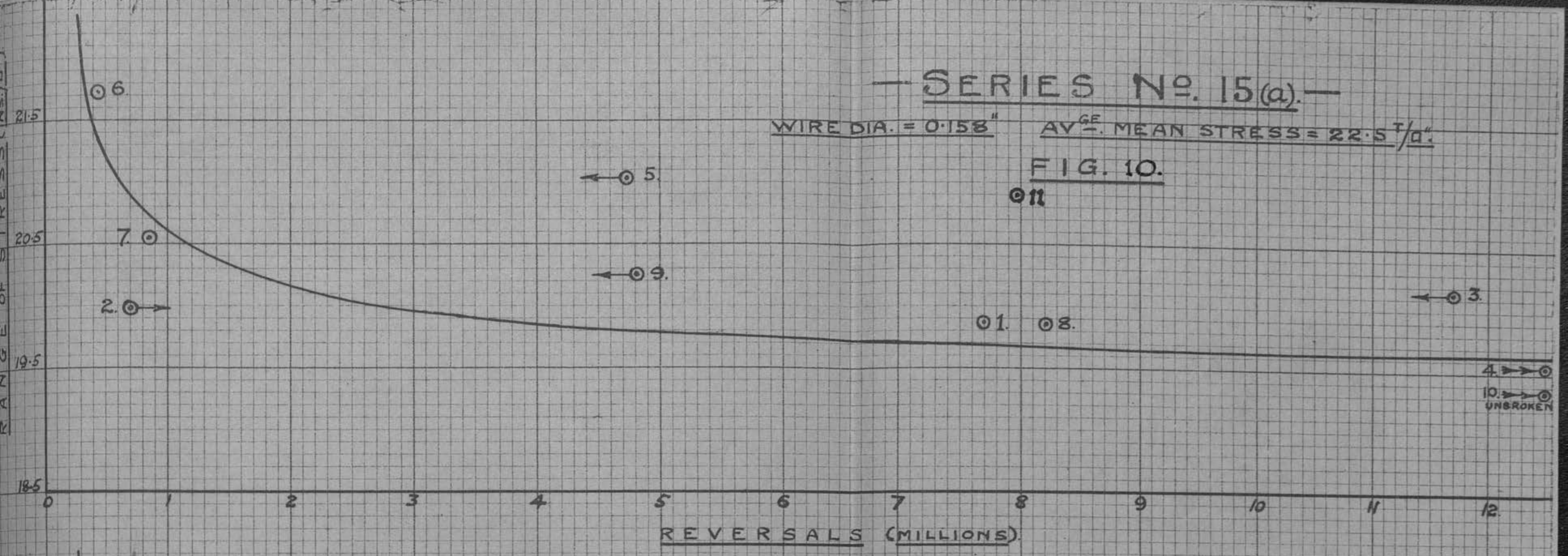


—SERIES No. 5(a).—

WIRE DIA. = 0·127". No. OF EFFECTIVE COILS = 4.

FIG. 7.

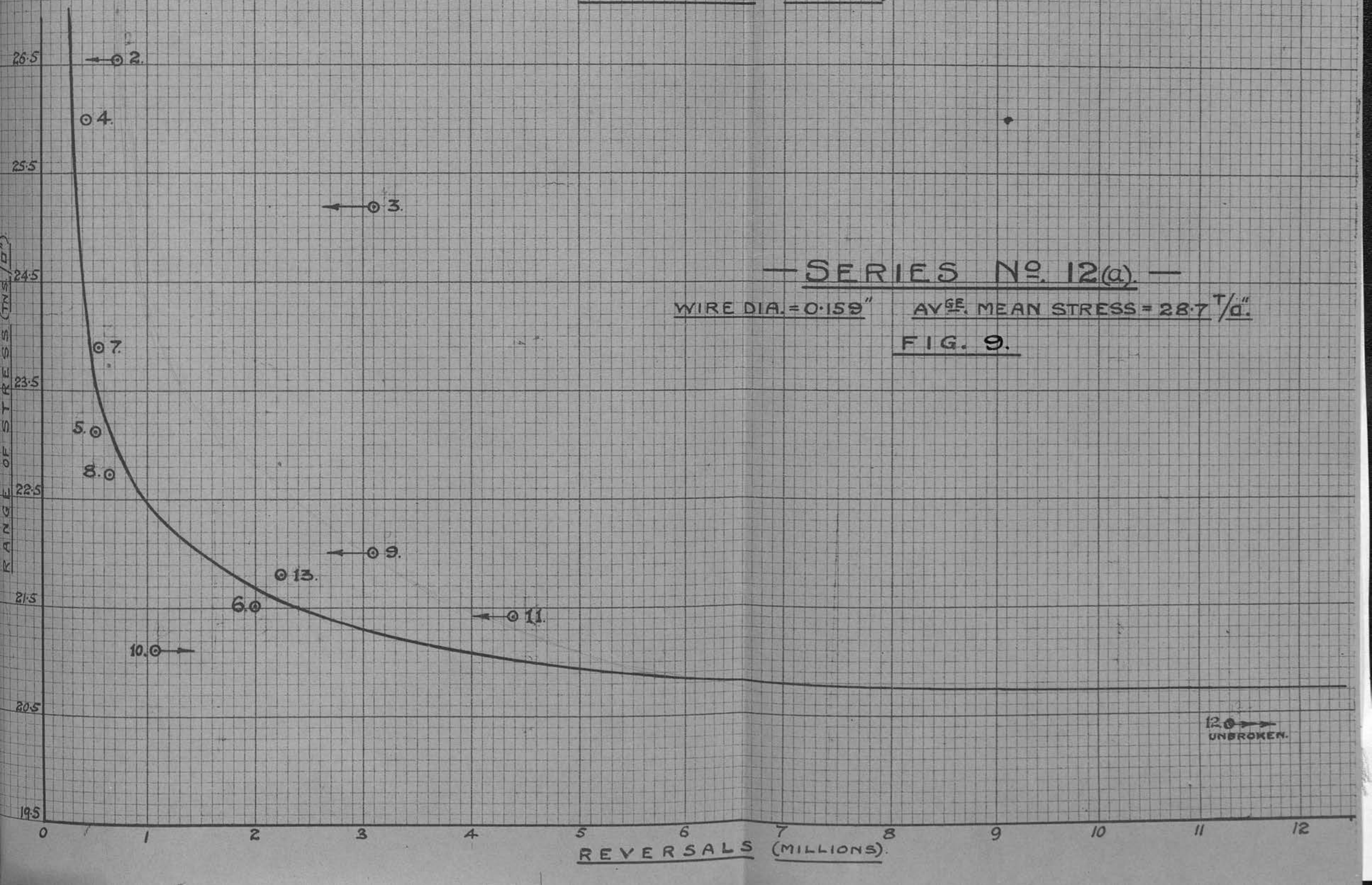




—SERIES No. 15(a).—

WIRE DIA. = 0·158" AV^{GE}. MEAN STRESS = 22·5 T/□".

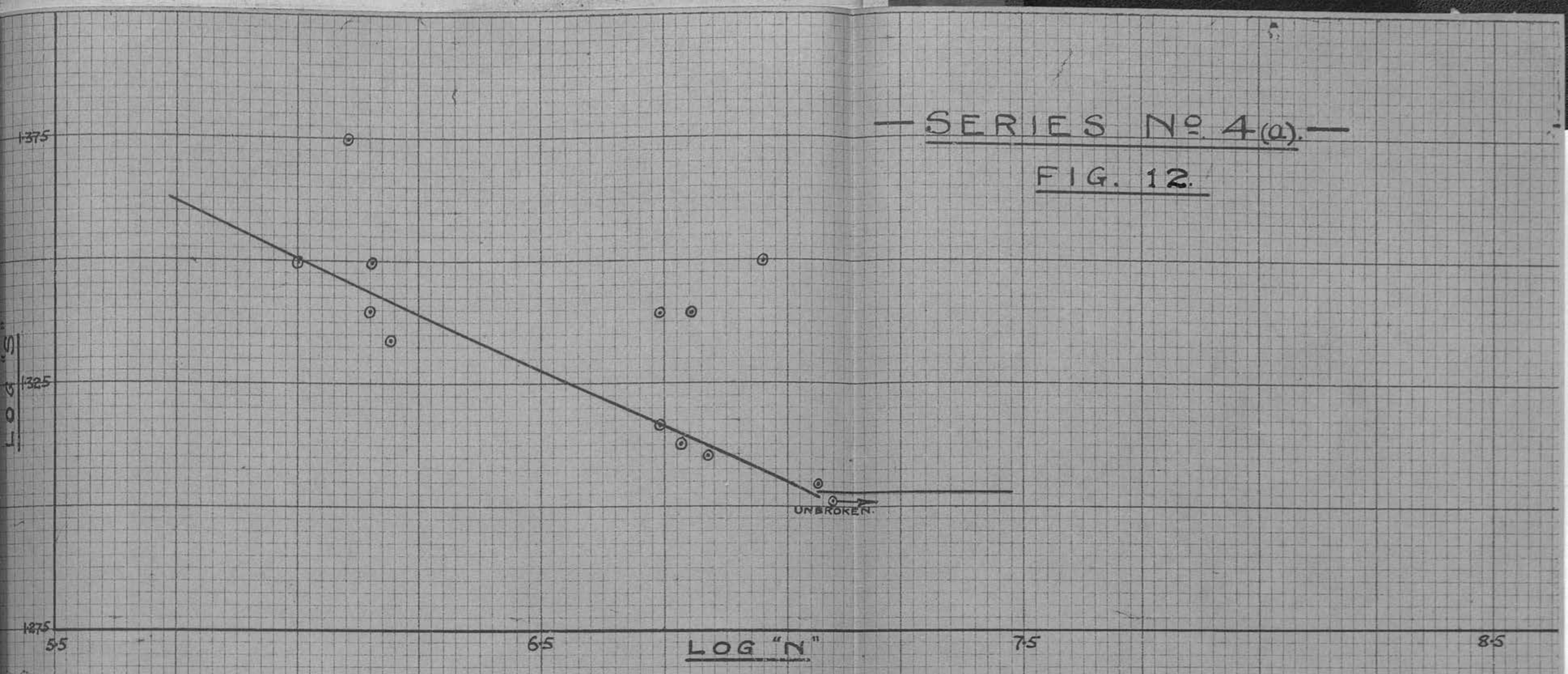
FIG. 10.



—SERIES No. 12(a).—

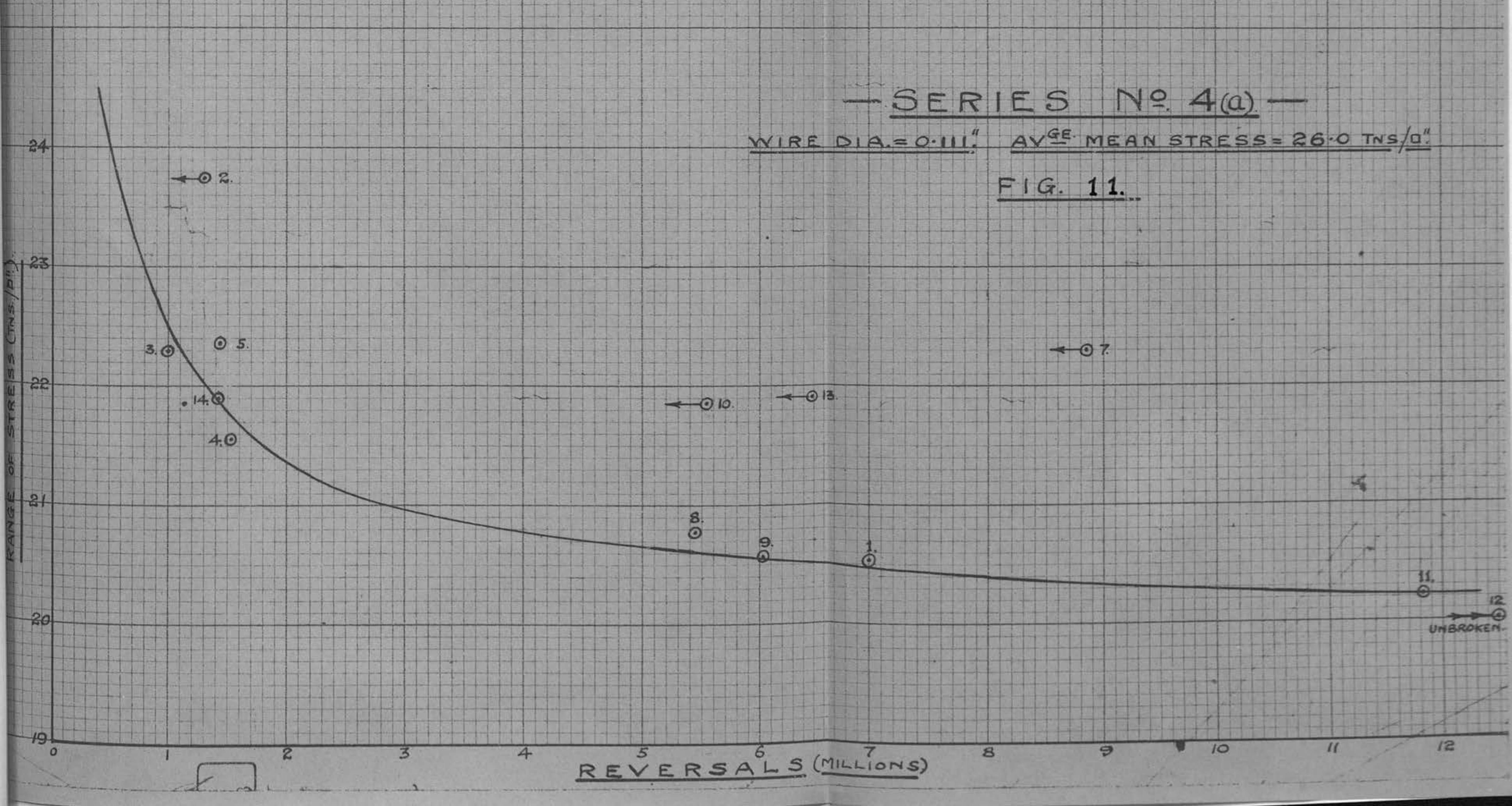
WIRE DIA. = 0·159" AV^{GE}. MEAN STRESS = 28·7 T/□".

FIG. 9.



— SERIES No. 4(a). —

FIG. 12.



— SERIES No. 4(a) —

WIRE DIA. = 0·111" AV^GE. MEAN STRESS = 26·0 TNS/□"

FIG. 11.